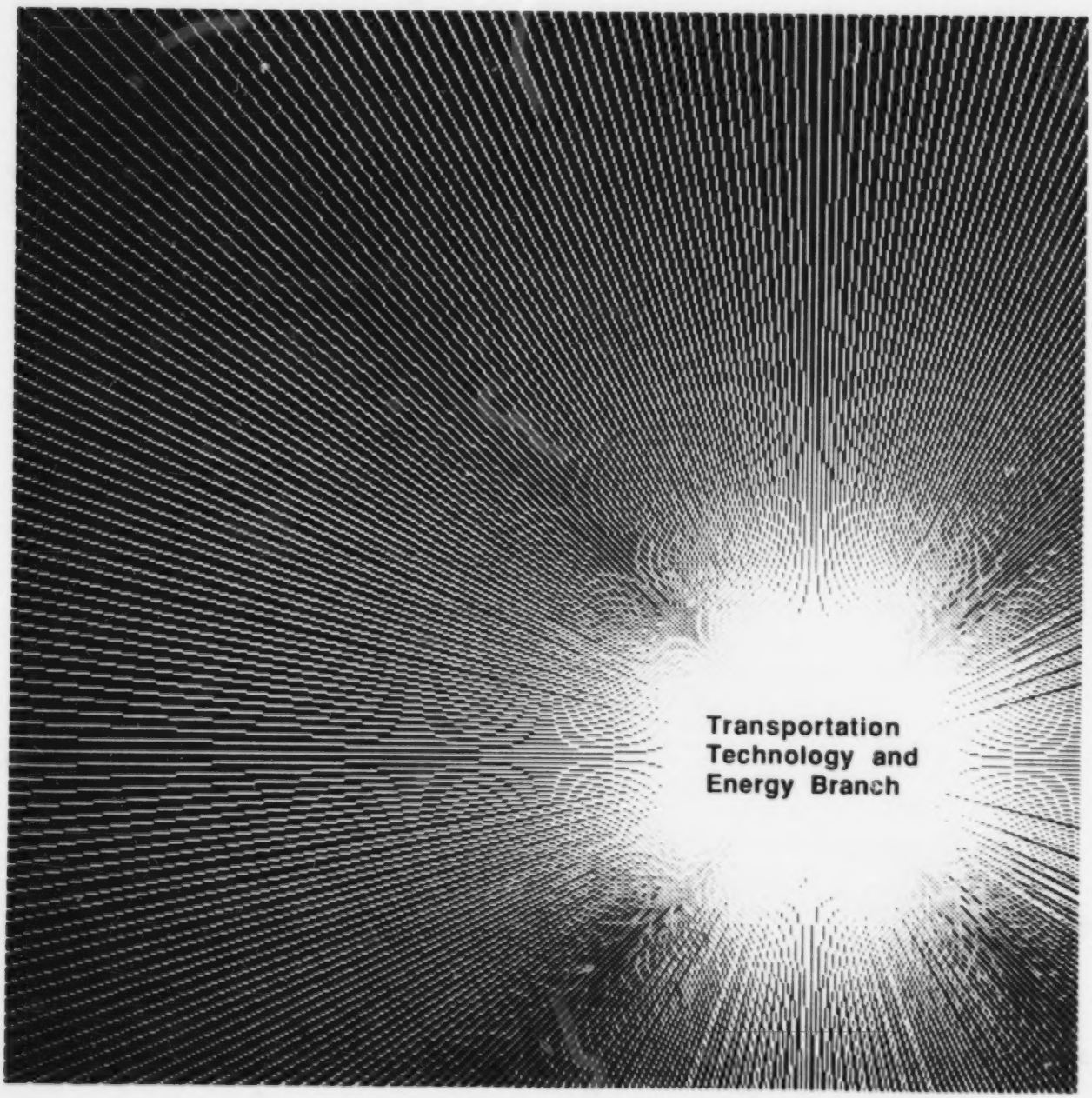
Ontario

Ministry
of
Transportation

Transportation
Technology and
Energy Branch



Evaluation of Compressed Natural Gas Conversion Systems

AF-88-03

AF-88-03

Evaluation of Compressed Natural Gas Conversion Systems

T. Topaloglu
Head
Automotive Energy Section
Automotive Technology and Systems Office

Published by:
The Transportation Energy Management Program (TEMP)

The Transportation Technology and Energy Branch
Ontario Ministry of Transportation
Ed Fulton, Minister

Ontario Ministry of Energy
Robert Wong, Minister

Published without prejudice
as to the application of the findings.
Crown copyright reserved; however, this
document may be reproduced for non-commercial
purposes with attribution to the Ministry.

For additional copies, write:
Transportation Technology and Energy Branch
Technical Publications
Ontario Ministry of Transportation
Room 321, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8
(416) 235-3466

August 1988

Technical Report Documentation Page

MTC Report Number AF-88-03	ISBN Number:	Other Document Number:	Date: Aug. 1988
Title: Chassis Dynamometer Evaluation of Compressed Natural Gas Conversion Systems			
Authors (name, title and/or organization): T. Topaloglu, Head, Automotive Energy Section			
Published by: Transportation Energy Management Program Transportation Technology and Energy Branch, MTO		**Client Group:**	
Participating Agencies:			

Abstract:
The performance of commercial compressed natural gas automotive conversion equipment is evaluated on the bases of fuel consumption, exhaust emissions, and acceleration performance results obtained in the MTO chassis dynamometer laboratory. The conversion equipment was supplied by the Diversified Fuel Components and CNG Fuel Systems companies of Ontario and was installed on a 5-L spark-ignition engine in a Ford F-150 pickup truck, which was operated as a CNG/gasoline dual-fuel vehicle.

Key Words: compressed natural gas, chassis dynamometer test, fuel consumption, exhaust emissions, acceleration performance

Comments:

Distribution: by request

Copyright Status: Crown copyright

TABLE OF CONTENTS

	PAGE
ACKNOWLEDGEMENTS	iv
EXECUTIVE SUMMARY	v
1/ INTRODUCTION	1
2/ BACKGROUND	3
3/ TEST PROGRAM	8
3.1/ Test Vehicle.	8
3.2/ Conversion Systems.	8
3.3/ Test Fuels.	10
3.4/ Test Methods.	11
4/ DISCUSSION OF TEST RESULTS	13
4.1/ Gasoline Consumption in the Baseline and Dual-Fuel Modes.	13
4.2/ Natural Gas Consumption and Its Comparison with Gasoline Consumption	14
4.3/ Acceleration Performance in the Baseline and Dual-Fuel Modes.	15
4.4/ Exhaust Emissions in the Baseline and Dual-Fuel Modes	16
4.5/ Effects of the Removal of Exhaust Emission Control Measures	18
4.6/ Effects of Dual-Curve Ignition Control Devices.	20
5/ COMPARISON OF RESULTS WITH ENGINE DYNAMOMETER AND FLEET TEST DATA	23
6/ CONCLUSIONS	25
7/ REFERENCES	27

LIST OF TABLES

PAGE

1/ Some Physical and Combustion Properties of Methane 29
2/ Vehicle Specifications 30
3/ Baseline Vehicle Diagnostics 30
4/ Test Fuel Specifications 31
5/ Dynamometer Parameters 32
6/ Gasoline Consumption and Performance of the Test Vehicle (MTO Chassis Dynamometer Test Results) 33
7/ Natural Gas Consumption and Performance of the Test Vehicle (MTO Chassis Dynamometer Test Results) 34
8/ Energy Consumption with Gasoline and Natural Gas (Consumption of Energy Utilization Efficiencies) 35
9/ Exhaust Emission Levels with Gasoline (MTO Dynamometer Test Results). 36
10/ Light-Duty Vehicle Exhaust Emission Standards. 36
11/ Exhaust Emission Levels with Natural Gas (MTO Dynamometer Test Results 37
12/ Effects of the Removal of Specific Exhaust Emission Control Measures in the Natural Gas Mode with the DFC Conversion Kit 38
13/ Effects of Ignition Control Device (ICD) in Gasoline Mode (MTO Chassis Dynamometer Test Results). 39
14/ Effects of Ignition Control Device (ICD) in Natural Gas Mode (MTO Chassis Dynamometer Test Results). 40

LIST OF FIGURES

1/ Air-Fuel Mixer of the Diversified Fuel Components Co 41
2/ Spark-Timing Curves of Baseline Gasoline Vehicle 42
3/ Spark Timing of Dual-Fuel Vehicle in the Gasoline Mode . . . 43
4/ Spark Timing of Dual-Fuel Vehicle in the CNG Mode. 44
5/ City (Urban) and Highway Driving Cycles. 45
6/ Gasoline Consumption in the Baseline and Dual-Fuel Modes . . 46
7/ Comparison of Natural Gas and Gasoline Combustion Efficiencies 47
8/ Energy Consumption with Gasoline and Natural Gas 48
9/ Hydrocarbon Emissions with Gasoline and Natural Gas 49
10/ Carbon Monoxide Emissions with Gasoline and Natural Gas. . . 50
11/ Nitrogen Oxide Emissions with Gasoline and Natural Gas . . . 51
12/ Variation of the Air-Fuel Mixture Equivalence Ratio (ϕ) with Vehicle Speed (Baseline Gasoline Mode). 52
13/ Variation of the Air-Fuel Mixture Equivalence Ratio (ϕ) with Vehicle Speed (Dual-Fuel Vehicle in Gasoline Mode). . . 53
14/ Variation of the Air-Fuel Mixture Equivalence Ratio (ϕ) with Vehicle Speed (Dual-Fuel Vehicle in the Natural Gas Mode). 54

ACKNOWLEDGEMENTS

This report has been made possible by the funding and support of the Ministry of Transportation and the Ministry of Energy.

The author is grateful to Norman Perfect, Matthew Tsang, George Egri, and Mahabir Singh for their contributions in the experimental work, to Ms. Ann Marshall for her editorial contribution, and to Mr. Ovi Colavincenzo for his many constructive suggestions.

EXECUTIVE SUMMARY

In this report, the performance of commercial compressed natural gas (CNG) automotive conversion equipment is evaluated on the bases of fuel consumption, exhaust emissions, and acceleration performance results obtained in the Ministry of Transportation (MTO) chassis dynamometer laboratory. The conversion systems were supplied by the Diversified Fuel Components (DFC) and CNG Fuel Systems (CFS) companies of Ontario and were installed on a 5-L spark-ignition engine in a Ford F-150 pickup truck, which was operated as a CNG/gasoline dual-fuel vehicle.

Fuel consumption and exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) were measured on gasoline, before and after conversion, and on natural gas over urban and highway driving cycles, strictly according to Transport Canada guidelines and US Environmental Protection Agency (EPA) regulations.

The chassis dynamometer results indicate that the conversion systems obtained from the two suppliers provided comparable performances. Energy consumption with natural gas was only 2.5% higher than with gasoline during both urban and highway driving. Acceleration performance with natural gas was 15 to 20% inferior to that with gasoline, as measured over 0 to 100 km/h acceleration tests. Emissions of CO and NO_x were lower with natural gas; however, emissions of HC were higher than with gasoline. All of these results were obtained with the original vehicle pollution control equipment in good operating order.

Specific tests were conducted to quantify the effects of disabling pollution control equipment, viz., the air pump and the exhaust gas recirculation (EGR) systems. Both measures resulted in unacceptably high exhaust emissions and no measurable benefits in either acceleration performance or fuel consumption.

This test program, in a limited sense, points to specific deficiencies with the present after-market conversion method, which may be alleviated by industry. The major deficiencies are the significant losses in power and energy efficiency with conversion in both natural gas and gasoline modes. Dedicated natural gas engines, with higher compression ratios and better fuel metering and ignition controls, are expected to mitigate these deficiencies and to enhance the attractiveness of natural gas as an alternative fuel.

1/ INTRODUCTION

Canadian federal and provincial governments are actively supporting the substitution of petroleum by natural gas, which is in surplus in this country. These efforts have succeeded in the residential, commercial, and industrial sectors, where equipment conversions have significantly reduced the demand for petroleum products. More recently, attention has been directed to the transportation sector, which is almost entirely dependent on petroleum.

In an effort to stimulate public interest in natural gas as a transportation fuel, a number of government-sponsored fleet demonstrations were staged in Ontario. These demonstrations provided, in addition to publicity, hands-on experience with all aspects of natural gas utilization. This experience, in turn, led to the conclusion that the introduction of natural gas to the transportation sector will strongly benefit from technical improvements in on-board vehicle conversion equipment, such as carburetion, ignition, and fuel storage components, and in such off-vehicle equipment as natural gas compressors, liquefiers, and dispensers. Therefore, the Ontario Ministry of Transportation undertook to support and conduct research and development (R&D) projects in a number of these areas. The results of one of these projects dealing with the evaluation of vehicle conversion equipment is presented in this report.

In this project, the compressed natural gas (CNG) conversion systems distributed by Diversified Fuel Components (DFC) (formerly Alternative Fuel Systems) and CNG Fuel Systems (CFS) companies were installed and tested on a Ford F-150 pickup truck. These are the two major CNG conversion equipment distributors in Ontario who have supplied equipment to the Consumers' Gas and Union Gas companies. With both conversion systems, the vehicle was operated as a CNG/gasoline dual-fuel vehicle.

The scope of the study was suggested by the natural gas industry, who expressed the need for reliable estimates of the natural gas consumption of typical road vehicles equipped with commercial conversion systems. Most of the estimates available to the industry are based on fleet data which lack consistency and reliability. Some of the information comes from biased sources, who claim substantial improvements in energy conversion efficiency. Although a few extensive scientific studies have been conducted during the 1970s with natural gas, using engine and chassis dynamometers, these are aimed largely at investigating the potential of natural gas as a means of reducing pollutant emissions from road vehicles. A significant portion of this work, which is reviewed in Section 2 of this report, dealt with the inherent characteristics of natural gas as

an engine fuel rather than with the specifics of engines and conversion systems. Neither one of the conversion systems tested for the present report has been used in any of these studies.

The work reported here is based on a series of dynamometer tests conducted at the MTO chassis dynamometer facility. The fuel consumption, acceleration performance, and exhaust emissions of the test vehicle were measured before the first conversion took place. This test series provided the "baseline" characteristics against which all subsequent results could be compared. After each conversion, the same vehicle parameters were determined with the converted dual-fuel vehicle on both natural gas and gasoline. This procedure allowed the assessment of the conversion systems in the natural gas and gasoline operating modes. The resulting data can be used to assess the suitability of natural gas as a transportation fuel, given the status of present conversion hardware and methods.

Claims have been made that, with natural gas, exhaust emission control equipment can be disabled to reduce fuel consumption without exceeding the Canadian emission standards. To unequivocally verify these claims, two of the major emission control measures of the test vehicle were independently disabled, and the resulting effects on fuel consumption, acceleration performance, and exhaust emission levels were measured. Further chassis dynamometer tests were conducted to assess the benefits of dual-ignition devices, one of which was incorporated into the test vehicle with the first conversion. This electronic device, made by Autotronics Control Corp. of Texas, produces two distinct timing schedules, one for natural gas and one for gasoline combustion.

2/ BACKGROUND

Although gaseous fuels, such as coal gas, were among the first to be considered for internal combustion engines, the advent of petroleum-based liquids has relegated them in most countries to stationary applications. Only in a few countries, notably Italy and Holland, have natural gas (NG) and liquefied petroleum gas (LPG) been used as transportation fuels, since approximately World War II. In the rest of the world, serious interest in gaseous fuels began as late as in the 1970s, in response to concerns with pollution and petroleum shortages.

Both natural gas (mainly methane) and liquefied petroleum gas (mainly propane) can be used in spark-ignition and, to a lesser extent, compression-ignition engines. The main reason for their failure as a transportation fuel is the lower energy density (Table 1). In compensation, they have higher octane ratings and cleaner exhaust emissions.

The performance of gaseous fuels in internal combustion engines has been assessed in a few studies employing single-cylinder engines [1-5]. Some of this work serves to define the ignition, knock, and auto-ignition limits of fuel-air mixtures as a function of major operating parameters, such as the compression ratio and air-fuel mixture equivalence ratio, ϕ. More recently, Karim and Wierzba [6] discussed this information and concluded that methane is highly resistant to knock. In addition, they presented power output, average combustion duration, and optimum spark-timing data for methane, propane, and methane-propane mixtures as a function of the equivalence ratio. These data, which were obtained with a Co-operative Fuel Research (CFR) engine at a compression ratio of 8.5:1, confirm the expectations that, with methane, minimum combustion duration is obtained with a stoichiometric mixture, while maximum power is delivered typically with 5 to 10% rich mixtures. The optimum spark timing is at its minimum at an equivalence ratio of approximately 1, and it increases by 2 to 3° as the mixture is leaned by 20%.

Evaluations of complete fuel systems rather than the fuel alone were published in the early 1970s by Genslak [7] and Fleming and Allsup [8]. These studies were carried out primarily to assess the potentials of natural gas and propane as means of reducing exhaust emissions of hydrocarbons (HC) and carbon monoxide (CO). In both studies, commercial carburetion systems were used, and the effect of engine parameters on exhaust emissions, performance, and fuel consumption were measured.

Genslak's work [7] included engine and chassis dynamometer tests, as well as road tests with 1970 Chevrolet 5.7 L engines. In the engine dynamometer experiments, NG-air mixtures were prepared in a non-commercial labor-

atory system designed to minimize air/fuel (A/F) ratio variations. In the chassis dynamometer tests, on the other hand, a commercial dual-fuel system was used in a 1970 Chevrolet Biscayne.

In the engine dynamometer experiments, the minimum advance for best torque (MBT) spark timing at wide open throttle (WOT) operation and with leanest for best torque (LBT) NG-air mixtures was determined to be 5° advanced relative to that with gasoline-air mixtures. In commercial installations where air-fuel mixtures are leaner than at the LBT setting, the magnitude of the spark advance would be larger. Peak performance with NG was found to be approximately 5% lower than with gasoline at MBT spark timing and LBT mixture strength (A/F ~ 15/1). An increase in A/F to 19/1 decreased peak power by a further 18% [7]. In addition, essentially equal thermal efficiencies were observed for natural gas, propane, and gasoline. Differences in power were attributed largely to differences in fuel density, along with differences in vehicle systems, such as the air-fuel induction system.

In the chassis dynamometer experiments, the exhaust emissions of the 1970 Chevrolet Biscayne were measured at several A/F, spark timing, and percent exhaust gas recirculation (EGR) combinations. The A/F ratio was varied by controlling the regulator final-stage pressure at the inlet of the gas mixer. The results indicated that the effect of the A/F ratio on exhaust emissions is similar to that with gasoline. The spark advance appeared to strongly influence levels of oxides of nitrogen (NO_x). Hydrocarbon levels were influenced only weakly, while CO levels were not influenced at all. As expected, greater spark advance caused an increase in NO_x and HC levels. Exhaust gas recirculation had a profound beneficial effect on NO_x emissions.

Fuel economy, driveability, and acceleration performance were evaluated by road testing on the General Motors (GM) proving ground. Natural gas consumption was measured over the California seven-mode city driving cycle and at steady speeds of up to 110 km/h by monitoring the pressure in the fuel tank. In these tests, the standard centrifugal spark advance curve was used, with a basic advance setting of 8° before top dead centre (BTDC). Vacuum advance was provided when desired with an adjustable vacuum unit. With no vacuum advance, the distributor provided 18° advance at 50 km/h on the 25 to 50 km acceleration mode in the city cycle. Two levels of vacuum advance were evaluated. At these levels, and at the just noted reference condition, total spark advance was noted to be 33 and 46° BTDC.

The fuel consumption tests revealed that the peak efficiency attainable with the CNG car was 13% lower than that with the comparable LPG car.

Genslak [7] attributed this to conversion system differences rather than to differences in fuel characteristics. Maximum fuel economy was obtained at an equivalence ratio of approximately 1.10, i.e., with a 10% lean mixture. Fuel economy was found to decline by 5 to 10% when no vacuum advance was applied. Introduction of EGR was also found to be detrimental to fuel economy; i.e., city fuel economy declined by approximately 10% with the introduction of EGR.

The driveability of the vehicles was evaluated on the test track over a fixed driving cycle. The test results indicated that driveability is acceptable with natural gas with full vacuum advance up to an A/F ratio of 19:1. In Genslak's [7] view, the best overall emission/driveability compromise was achieved with no vacuum advance and without EGR at $\phi = 1.12$. However, under these conditions the city fuel economy was noted to be 15% below its maximum value.

In the 0 to 100 km/h acceleration tests, the natural gas vehicle was found to suffer a 66% disadvantage; however, part of this was attributed to system differences, notably to the leaner (12%) carburetion of the CNG vehicle. It was noted that inclusion of a full-throttle enrichment device would largely mitigate this deficiency. In fact, according to Genslak [7], both fuel economy and acceleration could be improved by the redesign of the commercial conversion system.

Fleming and Allsup's [8] work included engine dynamometer tests with a single-cylinder and a multi-cylinder engine, as well as chassis dynamometer tests with six 1968 to 1970 vehicles. The results of this work, especially the engine dynamometer component, serve to assess the characteristics of NG rather than evaluate its time in modern vehicles by the application of commercial conversion systems.

The single-cylinder CFR engine was operated at a speed of 1800 rpm, an ignition timing of 30° BTDC, a compression ratio of 8:1, and a constant airflow rate. Under these conditions, the variation of exhaust emissions with the A/F ratio was determined in great detail. CO emission levels were found to be insensitive to the selection of the fuel. HC emissions were lower with natural gas at any A/F ratio. Emissions of NO_x peaked at an equivalence ratio of approximately 1.05 (slightly lean), and the maximum level was lower for natural gas than for gasoline. The lean misfire limit for natural gas was deemed to be greater than 1.45, which is a significant improvement over that of 1.3 for gasoline. At an equivalence ratio of 1.45, both HC and NO_x emission levels are relatively low. Thus, the ability to operate fuel leaner on natural gas has important pollution control ramifications. Another important benefit of natural gas is the lower chemical reactivity of the resulting exhaust gases,

which was assessed by Fleming and Allsup [8] to be 25% of that of gasoline. This result implies that widespread natural gas consumption would significantly diminish the photochemical smog problem.

In the multi-cylinder engine dynamometer tests, the effect of A/F and ignition timing on exhaust emissions and fuel consumption was determined with a 1969 5.4 L automotive engine at 1500 and 2500 rpm and road-load power settings. This engine was not equipped with any emission control devices, such as oxidation catalysts or EGR systems. The experimental setup included a mixing chamber installed between the carburetor and the intake manifold, and the exhaust crossover passage through the intake manifold was blocked. The results of this work indicate that CO emission is relatively independent of ignition timing, while HC and NO_x emissions, as well as specific fuel consumption, are rather sensitive to ignition timing at any A/F, but especially at A/F values between 19 and 20. In this A/F range, specific fuel consumption and HC emission are at their minimum; however, NO_x emission is at its maximum. In the same A/F range, advancing the ignition timing from 25 to 45° BTDC at 2500 rpm produces a fuel consumption decrease of the order of 10% and a large HC emission reduction. But NO_x emission sharply increases with timing advance because it results in higher peak combustion pressure and temperature. Thus, with natural gas, as with gasoline, there is a trade-off between fuel consumption and NO_x emission.

For the chassis dynamometer tests, the vehicles were equipped with commercial natural gas carburetors. The main objective was, again, the determination of the effects of A/F and ignition timing on exhaust emission levels and fuel consumption. As in the engine dynamometer tests, they displayed the greatest effect on NO_x emission, presenting a trade-off between emission versus fuel consumption and performance. HC and CO emissions with natural gas were found to be markedly lower than with gasoline.

In an additional series of experiments, Fleming and Allsup [8] investigated the effect of ambient temperature on exhaust emissions of natural-gas- and gasoline-fuelled vehicles over the ambient temperature range of -7 to 35°C. Unlike with gasoline, HC and CO emissions were found to be essentially constant with natural gas over the temperature range considered.

In another investigation, Marshall [9] used natural gas to minimize the fuel economy penalty associated with cold-start and warm-up operation at colder ambient conditions. The reported chassis dynamometer data were collected with two vehicles at -7 to +32°C. The natural gas carburetor was obtained from Dual-Fuel Inc., and A/F and spark timing were optimized

for minimum fuel consumption within the exhaust emission limits. The energy consumption of this optimized vehicle on natural gas was reported to be 15% less than on gasoline over an 10 km driving cycle at -7°C. Thus, the results of this study indicate a substantial energy conservation potential with natural gas under colder climatic conditions.

3/ TEST PROGRAM

The main objective of the test program was the accurate determination of the fuel consumption, acceleration performance, and exhaust emission characteristics of a typical North American commercial vehicle before and after conversion to natural gas operation, using conversion kits most commonly available on the Canadian market. A new Ford F-150 pickup truck was selected as the test vehicle, and Diversified Fuel Components (DFC) and CNG Fuel Systems (CFS) were the sources for the conversion kits. Fuel consumption, exhaust emissions, and performance were measured in the MTO chassis dynamometer facility according to the Transport Canada guidelines [10] and industry practices. These tests were carried out with the baseline vehicle and with the conversion systems, using both natural gas and gasoline. At the end of the program a further set of tests was conducted in the baseline configuration to detect any major change from the baseline measurements.

Fuel consumption and exhaust emissions were determined on urban and highway driving schedules, as well as in idle and cruise modes. In addition, air-fuel mixture strength and ignition timing were characterized both for the baseline and dual-fuel configurations of the vehicle.

Details of the test vehicle, conversion systems, test fuels, and test methods are presented in Sections 3.1 to 3.4.

3.1/ Test Vehicle

The test vehicle was selected to be a new Ford F-150 pickup truck equipped with a 4.9 L, six-cylinder, spark-ignition engine. This is a common commercial vehicle, which is also used in the MTO fleet. The main specifications of the test vehicle are provided in Table 2. Prior to chassis dynamometer testing, the vehicle was broken in on gasoline over approximately 7500 km of city and highway driving. The vehicle calibration parameters and their values are listed in Table 3.

3.2/ Conversion Systems

Conversion systems distributed by DFC and CFS were tested in this project. This involved testing two versions of the DFC kit and one CFS kit.

The main elements of the DFC system, which is approved by the Underwriters Laboratory of Canada (ULC), are the Italian-made Tartarini pressure regulator (Model RP/76) and the Canadian-made air-fuel mixer. The regulator is a three-stage unit with a built-in electric fuel-lock, a

primer, a power valve, and a pressure gauge. In addition, it includes a water jacket through which the engine coolant is circulated to prevent hydrate formation. The first stage of the regulator reduces the gas pressure to 245 kPa (35 psi); the second stage reduces it to 101 kPa (14.7 psi). The mixer vacuum is applied to the third stage to pull the gas through the carburetor.

The first stage of the regulator incorporates a safety valve designed to close if a diaphragm ruptures. Furthermore, the fuel-lock includes a vacuum switch which senses the loss of engine vacuum and closes the main CNG solenoid at the inlet to the first stage.

The primer solenoid allows fuel flow between the first and last stages. The power valve, on the other hand, allows supplementary fuel flow between the second and third stages of the regulator in response to WOT (wide open throttle) demand.

The air-fuel mixer used in this system is mounted over the gasoline carburetor and at the centre of the air filter. As illustrated in Figure 1, it contains a venturi ring with numerous holes in its periphery and a movable plate placed over it. Natural gas is dispensed through the venturi ring holes. The diameter of these holes and the distance between the plate and ring are matched to the engine displacement. In the gasoline mode, an electrically activated vacuum solenoid lifts the venturi plate and thus stops natural gas flow.

The first version of the DFC kit incorporates a power screw in the line between the regulator and the air-fuel mixer. The power screw serves to limit the maximum flow of natural gas. The second version incorporates a new air mixer with more precisely sized natural gas induction holes, eliminating the need for the power screw.

The vehicle conversion using the DFC kit was carried out by Consumers' Gas garage mechanics who were trained by DFC and had already converted 22 Consumers' Gas vans. The final "tune-up" of the DFC kit was done by DFC representatives.

The main elements of the CFS system are the Italian-made Renzo Landi regulator and air-fuel mixer. The TN2/C regulator used in this project is a three-stage unit which incorporates an idle adjustment, an electrically operated CNG shut-off valve, a primer, and a water jacket. This regulator, unlike the Tartarini unit, does not have a built-in power or enrichment valve. The air-fuel mixer is based on the venturi principle, and it is adjustable to match engine displacement. To limit maximum natural gas flow, a power screw is used in the low-pressure fuel line

leading to the mixer. This system was installed on the test vehicle by the CFS conversion shop.

The fuel storage system of the test vehicle includes two Taylor-Wharton high-pressure cylinders, which are Department of Transport (DOT) 3AA rated for 24.8 MPa (3500 psi) service. Each cylinder has a water capacity of approximately 44 L and a mass of 65 kg. The combined fuel capacity of the two cylinders is about 23 m^3 at 20.7 MPa (3000 psi) working pressure and 21°C. The two cylinders are mounted horizontally in the bed of the pickup truck, behind the driver's cab. Thus, all fuel lines and valves are located outside of the driver's cab. The high-pressure fuel lines are of seamless stainless steel, with a 9.5 mm outside diameter and a 1.25 mm minimum wall thickness.

In addition to the carburetion and fuel storage systems, the ignition system of the vehicle was modified by employing the Autotronic CNG/gasoline dual-curve ignition control unit. This unit modifies the distributor advance calibration when natural gas is selected as the fuel. Thus, the use of the dual-curve ignition controller allows the dual-fuel vehicle to operate on its baseline ignition timing schedule while gasoline is being used and to switch over to an advanced timing schedule for natural gas. The need for the advanced timing is dictated by the lower speed of combustion in natural-gas-air mixtures (Table 1). The timing schedules produced by the vehicles' original spark-timing mechanisms, as measured at MTO, with and without vacuum advance, are presented in Figure 2. The schedules produced by the dual-curve ignition system for gasoline and natural gas consumption, as measured at MTO, are presented in Figures 3 and 4, respectively. These figures indicate that the dual-curve ignition system affects mainly the base timing and does not substantially alter the shape of the timing schedule. The measured difference between the ignition schedules for gasoline and natural gas in base timing is approximately 18°, while the difference in total timing at higher engine speeds, i.e., at greater than 2000 rpm, is approximately 10°.

Both the fuel storage and the dual-curve ignition systems were common to all conversion systems tested.

3.3/ Test Fuels

The gasoline used in this test program was exclusively purchased from the nearest Shell station. It was the unleaded regular blend ("Shell Ultra"). Before each set of tests, the density of the gasoline in the vehicle fuel tank was measured. Its value was then used in the estimation of fuel consumption from the chassis dynamometer test data. The

average density for gasoline used throughout the test program was 0.740 kg/L, which suggests a lower heating value of 32.4 MJ/L (18 900 Btu/lb or 140 000 Btu/gal.). The boiling range distribution of a sample of the gasoline used is presented in Table 4.

The natural gas used in this program was initially purchased from the Consumers' Gas fuelling station at 405 Eastern Avenue in downtown Toronto. However, as soon as a public natural gas fuelling station was opened in West Toronto, natural gas was routinely obtained from this source. The composition of natural gas was periodically obtained from Consumers' Gas. The average fuel composition is reproduced in Table 4. Based on these data, the average lower heating value of the natural gas used in this program is estimated as 33.6 MJ/m^3 (903.1 Btu/ft^3).

These estimates of lower heating values for gasoline and natural gas result in an energy equivalence of 0.96 m^3 NG/L gasoline, or 154 ft^3 NG/ imp. gal. of gasoline.

3.4/ Test Methods

Vehicle fuel consumption, exhaust emissions, and performance were measured in the MTO test laboratory, which is equipped to perform chassis dynamometer tests according to Transport Canada guidelines [10] and the US Environmental Protection Agency (EPA) regulations [11]. The main pieces of hardware in the laboratory include a Clayton Model ECE-50 chassis dynamometer; a Horiba constant-volume sampling system; Horiba and Beckman HC, CO, CO_2, and NO_x emissions analysers; computerized data reduction facilities; and a Bechman Model 957 air-fuel ratio analyser. The dynamometer is equipped with an automatic road-load power control unit and a direct-drive variable inertial weight system with 1000 to 8750 lb range and 125 lb increments. Details of the test laboratory, the equipment therein, and the test procedures may be found in the MTO report LAB-81-01 [12].

Fuel consumption and exhaust emissions were measured over the Transport Canada city and highway test cycles described in Figure 5. The city cycle consists of three phases. The first phase (cold transient phase) involves a cold start and 505 s of driving. The second phase (stabilized phase) is driven immediately after the first phase, and its duration is 866 s. The engine is then turned off for 10 min, after which the first 505 s of the test are repeated. This last segment of driving constitutes the hot transient phase. Vehicle exhaust emissions are measured individually for each phase. To ensure repeatability and representativeness, the city cycle is preceded by a preconditioning step, which includes

driving the vehicle on the dynamometer over a complete test cycle and then storing it for 12 to 36 h under controlled conditions (20 to 30°C).

For the highway fuel consumption and emissions testing, the vehicle is driven twice over the 765 s driving cycle, shown in Figure 2. The first run constitutes preconditioning -- no exhaust gas sample is required here. This run is followed by a 15 s idle period and the second run, during which these exhaust gases are sampled and analysed.

In all fuel consumption tests (i.e., city, highway, cruise, and idle tests), the concentrations of HC, CO, carbon dioxide (CO_2), and NO_x are measured accurately. These measurements are then used in a mass balance (carbon balance) to determine vehicle fuel consumption under standard ambient conditions.

The dynamometer parameters applicable to the city and highway tests are summarized in Table 5. The inertia weight and actual road-load values are obtained from the US EPA Emissions Test Laboratories. The test cell temperature, pressure, and humidity recorded in Table 4 are used in the prediction of exhaust emissions and fuel consumption under standard ambient conditions.

Vehicle acceleration performance was estimated by measuring the time period necessary to accelerate from 0 to 100 km/h on the dynamometer.

4/ DISCUSSION OF TEST RESULTS

In the test program outlined in Section 3, experimental data were obtained with a Ford F-150 pickup truck in baseline and CNG/gasoline dual-fuel configurations, using the conversion equipment of DFC and CFS. The data include fuel consumption, exhaust emissions, acceleration time, ignition timing, and air/fuel ratio measurements. In what follows, these data are used to assess the performance of natural gas as a transportation fuel in a typical application, using the two makes of conversion kits most commonly purchased in Ontario. In addition, the effect of disabling specific exhaust emission control devices and the utility of the dual-curve ignition control unit are investigated.

4.1/ Gasoline Consumption in the Baseline and Dual-Fuel Modes

The assessment of natural gas as a transportation fuel has to involve a comparison with gasoline. To this end, series of tests were carried out with gasoline before and after vehicle conversion.

The first test series provided the baseline data against which all results obtained with gasoline and natural gas are compared. In the next two test series, using gasoline as fuel, the vehicle was equipped with the DFC and CFS conversion kits, respectively. The fuel consumption and acceleration performance results of these tests are presented in Table 6. These results indicate that the average fuel consumption of the baseline vehicle is 14.63 L/100 km on the urban and 12.10 L/100 km on the highway driving cycles. The combined fuel consumption figure representing 55% urban and 45% highway driving is 13.49 L/100 km, which is only 3 to 4% higher than the 13.0 L/100 km figure provided in the Transport Canada fuel consumption guides. The source of the Transport Canada figures is most likely the vehicle manufacturer.

The data obtained in the dual-fuel mode and summarized in Table 6 indicate that the two kits have very similar effects on fuel consumption. Therefore, it is appropriate to compare the average values of these results with the baseline data, as is done in Table 6 and in Figure 6. This comparison reveals that the kits deteriorate vehicle fuel consumption by approximately 8% under urban driving conditions. However, they do not affect highway fuel consumption. The idle and 50 km/h cruise test data show fuel consumption increases of 25.4 and 4.6%, respectively.

Furthermore, the main contribution to the urban fuel economy decline appears to take place under cold-start and warm-up conditions, as indicated by the 17.1% increase in the cold transient-phase fuel-consumption

readings in Table 6. This would suggest that in city driving, especially when small trips and excessive idling is involved, the use of gasoline in dual-fuel vehicles would entail significant fuel losses.

4.2/ Natural Gas Consumption and Its Comparison with Gasoline Consumption

In this project, the Ford F-150 pickup truck was retrofitted and tested with two versions of the DFC kit and the CFS kit. The natural gas consumption data obtained in these three configurations are summarized in Table 7 and will be used to compare the conversion kits considered and to reduce the relative energy efficiency of natural gas combustion.

As is evident at first glance, the three kits resulted in very similar natural consumption figures. Specifically, in all driving modes, except at 100 km/h cruise, the difference in fuel consumption in m^3/100 km is within 2 to 3%. Although the differences are small, they are statistically significant, at a 99% level, thanks to the relatively small test-to-test variations in results and the large number of repeat experiments conducted. Thus, it appears that there is a small difference between the kits tested as far as fuel consumption in urban and highway driving is concerned. However, even exogenous factors, such as the vehicle's odometer reading at the time of the test and unit-to-unit variations in the same make of conversion kits, may account for a 2 to 3% difference in fuel consumption. Therefore, this should not be the basis for equipment selection.

It is difficult to compare directly the efficiency of natural gas combustion with gasoline combustion by simply looking at the fuel consumption results, because the two fuels have very different energy densities. One method of comparison is applied in Figure 7, where average natural gas consumption values for the urban and highway driving cycles, as well as for 50 and 100 km/h cruise tests, are plotted against the corresponding gasoline consumption values. In this figure, the fuel equivalence takes the form of a straight line with slope 0.96 m^3 NG/L gasoline, and the relative efficiency of a natural gas conversion in a given driving mode is indicated by the vertical separation of the corresponding data point from this line. The data of this study, in Figure 8, suggest that there is only a slight deterioration in efficiency with natural gas. The same conclusion is reached by considering Table 8, in which the energy consumption in each driving mode is tabulated. These figures were derived from the fuel consumption data by using the lower heating values of the two fuels provided in Section 3.2.

According to the results in Table 8, the average energy consumption realized with the three conversion kits is approximately 2.5% higher than that with the baseline gasoline vehicle in both urban and highway driving. In the cruise modes, 3.5 to 4.5% more energy appears to be consumed with natural gas. However, at idle, this trend is reversed and 10 to 11% less energy is consumed with natural gas.

The energy consumption in the gasoline mode of the converted vehicle is also included in Table 8. This information allows comparison of the efficiencies of the dual-fuel vehicle on natural gas and gasoline. This comparison indicates that, on the average, the converted vehicle is more efficient on natural gas than on gasoline. This advantage is 4.7% in urban driving, 2.2% in highway driving, and as much as 30% at idle. Thus, although the conversion of the vehicle resulted in a deterioration of its energy efficiency, the decrease is very small in the natural gas mode, as already indicated.

4.3/ Acceleration Performance in the Baseline and Dual-Fuel Modes

The acceleration performance of the test vehicle was assessed by measuring the minimum time required to reach 100 km/h from standstill. This entailed full-throttle acceleration in drive and second gears. The averaged test results are provided in Tables 6 and 7 for gasoline and natural gas combustion, respectively.

The results in Table 6 indicate that the conversion process may produce a small change in acceleration performance on gasoline. With the DFC kit (second version), this change is a 9 to 10% increase in performance, whereas with the CFS kit, a 13 to 19% decrease. The conversion kits inevitably add more restriction to airflow in the induction system of the engine, which, with everything else remaining unchanged, would produce a decline in performance. However, since the conversion systems affect fuel flow and ignition timing as well, the overall effect of a specific system, such as the DFC one, may be an improvement in performance.

The switch to natural gas is expected to result in a noticeable decline in acceleration performance. Indeed, comparison of the test results in Tables 6 and 7 indicates that the dual-fuel vehicle operating on natural gas takes, on the average, 15 to 20% longer to accelerate from 0 to 100 km/h than the baseline gasoline vehicle. The difference is greater in the second gear than in the first gear performance, i.e., 20 versus 15%. The two makes of conversion systems have a similar impact on acceleration performance.

The loss of power observed with natural gas is largely due to its gaseous state. With a stoichiometric air-fuel mixture, natural gas displaces approximately 9% of the volume of air. Thus, on this basis, an 8 to 10% drop in WOT power and acceleration performance is expected. The greater loss in performance observed in this study may be partially due to additional volumetric efficiency losses caused by the NG carburetion equipment, the absence of charge cooling, and the smaller flame speed in natural-gas-air mixtures. The NG carburetion system adds to flow restrictions and increases the charge temperature, resulting in lower volumetric efficiency and acceleration performance.

4.4/ Exhaust Emissions in the Baseline and Dual-Fuel Modes

The exhaust emissions of HC, CO, and NO_x were measured strictly according to the Canadian and US federal governments' test procedures specified in References 10 and 11. The urban and highway test cycles prescribed in these test procedures are illustrated in Figure 5. The Canadian and US exhaust emission standards relate to only the urban cycle, which is commonly referred to as the CVS-CH cycle. This cycle incorporates cold transient, stablilized, and hot transient phases representing trips from a cold start, extended driving, and a warm start, respectively. The exhaust emission levels for the total urban cycle are determined by weighting those for the three cycles, according to the estimated fraction of each type of trip made in North America.

The levels of HC, CO, and NO_x emissions are quantified in terms of the mass of each pollutant exhausted per unit distance. The engineering units selected for this quantify are those specified in the standards, i.e., g/mi.

The exhaust emission results with the baseline vehicle are presented in Table 9. The HC, CO, and NO_x levels over the urban cycle were 0.54, 3.76, and 1.57 g/mi, respectively. These are well within the present Canadian light-duty exhaust emission standards reproduced in Table 10. In fact, it is apparent that this vehicle is designed to meet the much more stringent US emission standards. The highway HC, CO, and NO_x levels were 0.13, 2.24, and 2.81 g/mi, respectively. As expected, under highway driving conditions less HC and CO and more NO_x are emitted than under urban driving conditions.

The emissions of the dual-fuel vehicle were quantified in the gasoline and natural gas modes, with each of the conversion systems. In this phase of the study, the emission control systems of the vehicle were not tampered with. The results in the gasoline mode are presented in Table 9, and those in the natural gas mode, in Table 11. Comparison of

the emission data obtained in baseline and dual-fuel modes is provided in Figures 9 to 11 for HC, CO, and NO_x, respectively. In these figures, the average values of the results with the individual conversion systems are shown.

The effect of the vehicle conversion was noted to have significant effects on all emissions. HC emissions, which result from unburnt fuel, were adversely affected by the conversions, both in the gasoline and natural gas modes. The increase was more pronounced in the urban cycle and resulted in 2.83 g/mi emissions on natural gas, which exceeds the 2.0 g/mi Canadian standard. However, with natural gas, most of the unburnt fuel is methane, which has a very low reactivity and toxicity. Thus, the HC standards defined for gasoline may not be applicable to natural gas.

The effect of the conversion on CO emissions strongly depended on the specific conversion system considered. The second DFC system resulted in lower CO emissions than the CFS system. However, in general, the dual-fuel vehicle produced more CO on gasoline than on natural gas. In fact, with one of the DFC systems, the CO emissions on natural gas were only 10 and 63% of those measured in the baseline gasoline mode on the urban and highway driving cycles, respectively.

The effect of the conversion on NO_x levels was less pronounced. In the gasoline mode and on the urban driving cycle, the DFC system caused a slight increase in NO_x emission, whereas the CFS system caused a decrease. Exactly the opposite occurred in the natural gas mode; i.e., the DFC system caused an increase, and the CFS, a decrease in NO_x emissions.

In summary, the dual-fuel vehicle in its gasoline mode produced more HC and CO and less NO_x. In its natural gas mode, it produced more HC and less CO and NO_x.

In an effort to explain some of these observations, the air-fuel mixture equivalence ratio was measured as a function of vehicle speed. The results for the baseline gasoline and dual-fuel gasoline and natural gas modes are presented in Figures 12 to 14, respectively. The data in Figure 12 indicate that the baseline vehicle is calibrated to run approximately 10% richer at idle and slightly lean over the 40 to 100 km range. In the 0 to 30 km/h range the equivalence ratio could not be reliably determined because of large fluctuations during each measurement.

Figure 13 suggests that the conversion systems affect the performance of the gasoline carburetor. The notable effect is an enrichment of the

air-fuel mixture at the higher speeds, which may be due to the flow restriction introduced by the natural gas mixers.

Figure 14 shows that the DFC and CFS conversions, as adjusted by the suppliers, produce distinctly different air-fuel mixture compositions with natural gas. Specifically, the DFC system produces a stoichiometric to slightly lean mixture over the entire vehicle speed range, whereas the CFS system always produces a rich mixture, except at idle. Thus, in the natural gas mode, the test vehicle is calibrated to run leaner than in the baseline mode with the DFC system and richer than in the baseline mode with the CFS system.

These trends explain some of the experimental observations. The richer air-fuel mixture in the dual-fuel gasoline mode is responsible for the higher CO emissions with both the DFC and, especially, the CFS systems. It also contributed to the higher HC emission levels and the lower NO_x levels, especially with the CFS system. The effects of the A/F ratio trends on emissions in the natural gas mode are more difficult to explain, since this case includes more changes with respect to the baseline case. The very low CO emission levels (0.36 and 0.15 g/mi on the urban and highway driving cycles, respectively) with the DFC system are consistent with the leaner carburetion. Similarly, the urban and highway CO emission levels with the CFS system may be explained by the stoichiometric A/F ratio at idle and the relatively rich A/F ratios at higher vehicle speeds. However, the higher NO_x emission levels with the CFS system are not consistent with the richer carburetion.

4.5/ Effects of the Removal of Exhaust Emission Control Measures

In the conversion of gasoline vehicles to mono-fuel propane operation, exhaust emission control measures are, in many instances, disabled or removed. At present, this is not common practice in the after-market natural gas conversion industry, where only gasoline/natural gas dual-fuel vehicles are involved. However, with the expansion of the refuelling network, mono-fuel applications and tampering with exhaust emission control systems may become more common. In anticipation of this development, the two major exhaust emission control devices on the test vehicle, i.e., the EGR and air injection systems, were disabled. The effects of these actions on natural gas consumption, exhaust emissions, and acceleration performance were measured and compared with baseline measurements on natural gas. Throughout these experiments, the DFC conversion kit was used. It is worth noting that the results presented here strictly apply to dual-fuel vehicles and can serve only as indications of what to expect in future mono-fuel CNG vehicles.

The main purpose of the EGR system is to reduce NO_x emissions by reducing the peak combustion temperature in the engine. This is accomplished by diluting the air-fuel mixture with exhaust gases under high inlet manifold conditions. The exhaust gases, being inert, effectively increase the heat capacity of the air-fuel mixture and result in the reduction of the peak combustion temperature and pressure. This will reduce the rate of NO_x formation, but it may also reduce the thermodynamic efficiency of the engine. However, a loss of efficiency is observed with higher EGR rates.

The experimental data generated in this study are presented in Table 12. They indicate that, under all driving conditions, the effect of disabling the EGR system (plugging the EGR valve) is less than 1% and, therefore, statistically insignificant. Only at idle, when the inlet manifold pressure is the lowest and the EGR rate the highest, is a 6% reduction in the natural gas consumption observed. The effect on acceleration performance is also negligible.

The exhaust emission measurements indicate that the EGR system does not have a major effect on CO and HC emissions. However, as expected, its influence on NO_x emissions is very strong. Without EGR, NO_x emissions rise to 9.79 and 12.01 g/mi on the urban and highway cycles, respectively. At these levels, the test vehicle would be in gross violation of Canadian and US standards. Thus, disabling of the EGR system is not expected to yield any significant benefits in fuel economy and acceleration performance and will result in very high NO_x levels.

The air injection system introduces air into the exhaust system at a rate proportional to engine speed and exhaust flow rate. Thereby, an oxidative environment is produced in the exhaust system and the oxidation catalyst, which leads to the oxidation of CO and HC to CO_2 and water (H_2O). This is a very effective method of reducing CO and HC pollution by vehicles and is not expected to involve any major fuel economy or performance penalties.

As indicated by the data in Table 12, the only discernible effect of this action is the increase in HC and, especially, CO emission levels. The urban and highway CO emission levels were measured as 15.90 and 25.39 g/mi, respectively, which, although within the present Canadian emission standards, far exceed the US standards.

In summary, elimination of the EGR and air injection systems on gasoline vehicles in their conversion to either dual-fuel or mono-fuel CNG vehicles is expected to result in excessive NO_x and CO emissions without

any tangible improvements in either fuel economy or acceleration performance.

4.6/ Effects of Dual-Curve Ignition Control Devices

The role of dual-curve ignition control devices (ICDs) in dual-fuel vehicles is to supply individual spark-timing schedules for each fuel used: in this case, gasoline and natural gas. The need for this measure arises from the difference in the flame propagation or combustion speeds of gasoline and natural gas under engine operating conditions. The natural-gas-air flame propagates more slowly than the gasoline-air flame, as indicated by the data in Table 1. Consequently, spark timing in the natural gas mode should be advanced relative to that in the gasoline mode. This is accomplished by the use of dual-curve ignition control devices.

In this project, two representative dual-curve ignition devices, both made by the Autotronic Controls Corporation, were used in conjunction with the DFC and CFS conversion systems. The timing schedules generated by these two units were very similar, and in what follows, the results obtained with only the CFS conversion system will be presented.

The alternative to using dual-curve ignition control devices is to advance the static timing. This is the alternative adopted by most CNG vehicle owners. The degree of advance most commonly adopted is 10°, which is a good choice for natural gas, as shown by engine dynamometer test data to be discussed in Section 5.

The static advance has a major effect on maximum engine power, fuel consumption, combustion characteristics (detonation and preignition), and exhaust emission levels. Its selection depends on the fuel and, to a lesser extent, engine characteristics. The choice made in natural gas conversions is aimed at providing adequate power and fuel economy in the natural gas mode while avoiding engine knock in the gasoline mode.

In the present project, the two options of using a dual-curve ICD and advancing static timing by 10° were compared in both the gasoline and natural gas modes by conducting fuel consumption, exhaust emissions (urban and highway cycles), and acceleration performance tests. The results of these tests are discussed after a presentation of the spark-timing schedules employed in the tests.

The timing schedules or timing curves (with and without vacuum advance) of the test vehicle in its baseline gasoline configuration are presented in Figure 2 and those in the gasoline and natural gas modes (with the CFS

conversion system and the Autotronic ignition service), in Figures 3 and 4, respectively. Comparison of Figures 2 and 3 indicates that, in the gasoline mode, the dual-curve ICD is basically duplicating the ignition timing curve of the baseline configuration. The maximum deviation between the two timing curves is only 2°, with the dual-curve ignition system output being more advanced. Advancing the static or base timing by 10° results in almost a constant 10° advance throughout the engine speed range, as indicated by the data in Figure 3. Thus, without the ICD, the spark timing of the dual-fuel vehicle in its gasoline mode is always 10° advanced with respect to the original equipment manufacturer's design.

In the natural gas mode, substantially different timing schedules are observed, with and without the dual-curve ICD (Figure 4). Specifically, total timing (centrifugal and vacuum advance) with the ICD is 10 to 20° more advanced than without it. The gap in the timing schedules is largest in the lower engine speed range.

The effect of the dual-curve ICD on fuel consumption, exhaust emissions, and acceleration performance is quantified by the test results summarized in Table 13. According to these, the fuel consumption of the test vehicle increases significantly due to the timing changes made either by the application of the ICD or by advancing static timing. The ICD causes an 8.3% increase in fuel consumption on the urban cycle; however, it does not have a major effect on highway fuel consumption. The static timing change, on the other hand, has a large effect on highway fuel consumption (9.3%). The effect of both measures on the combined (urban and highway) fuel consumption figure is approximately 5%.

Acceleration performance in the gasoline mode is also adversely affected by the timing changes. In this respect, application of the ICD is less desirable since it causes a 13 to 19% deterioration in the 0 to 100 km/h acceleration time, whereas a base timing change of 10° results in a 5 to 8% deterioration only. HC and CO emissions in the gasoline mode are adversely affected, whereas NO_x emissions improve because of the ignition timing advance. However, they all stay within the Canadian exhaust emission standards.

These observations are consistent with a decline in engine peak pressure and temperature. This would result in lower thermodynamic efficiency, peak engine power, and NO_x emissions. It would also result in higher HC and CO conditions since the lower temperatures would result in lower oxidation rates.

The data obtained in the natural gas mode are summarized in Table 14. In this mode, the loss of efficiency relative to the baseline gasoline design is smaller, as was already noted in Section 4.2. The application of the ICD may not result in the most efficient combustion, because the combined fuel consumption figures indicate a 3.2% penalty. However, its application is justified on the basis of better acceleration performance. The 0 to 100 km/h acceleration periods measured with the ICD are approximately 10% smaller than those obtained with a 10° static timing advance. With respect to exhaust emissions, static timing advance only results in higher CO and HC and lower NO_x emissions.

In summary, the use of the dual-curve ICD was compared with advancing static timing by 10°. In general, the advantages of using the ICD appear to outweigh the disadvantages in the natural gas mode. The same is not true in the gasoline mode. Thus, the ICD tested cannot be recommended to all applications.

5/ COMPARISON OF RESULTS WITH ENGINE DYNAMOMETER AND FLEET TEST DATA

In parallel with the in-house chassis dynamometer project, MTO commissioned an engine dynamometer study at the University of Toronto and a fleet demonstration at the Consumers' Gas Co. in Toronto. The purpose of this three-pronged approach was to generate complementary data to assess and improve the acceptability of CNG and CNG conversion systems in light-duty vehicle applications. The engine dynamometer work [13] supplied the fundamental engine performance data required to assess and optimize the conversions (e.g., selection of A/F ratio and spark-timing schedules). The chassis dynamometer data allowed the quantification of fuel consumption and exhaust emissions over urban and highway driving cycles under controlled conditions. The fleet demonstration [14,15] supplied in-use operating experience with CNG/gasoline dual-fuel vehicles, as well as a typical CNG fuelling facility.

In the engine dynamometer project, the Ford 4.9 L six-cylinder engine used in the present study was tested with four CNG conversion systems, among which were those of the DFC and CFS companies. With the baseline gasoline engine and the converted CNG engine, the following were measured under a set of engine load and speed conditions:

- torque
- fuel consumption
- exhaust emissions of HC, CO, and NO_x
- the A/F ratio
- spark timing
- manifold vacuum
- exhaust port temperatures
- a number of other operating parameters

The results of this work were used to compare the performance of the four conversion systems with the baseline gasoline performance and to determine optimum A/F ratio and spark-timing settings for maximum power of full load and minimum fuel consumption at part load.

According to the engine dynamometer test results [13], conversion to natural gas with the four conversion kits tested produces a maximum power drop of 12 to 22%. This finding is in qualitative agreement with the acceleration time measurements of the present study. Similarly, engine efficiency deteriorates and fuel consumption increases significantly, except at a few specific engine operating points. With one of the poorer conversion systems, the increase in energy consumption (brake-specific energy consumption) with respect to the baseline gasoline configuration is 30 to 50% over the engine load and speed range investigated [13].

This is a much larger increase than observed in this study. The discrepancy suggests that in stabilized steady-state running, as is the case in the engine dynamometer tests, the efficiency of the engine is much lower on natural gas than on gasoline. On the other hand, under transient conditions, as is the case during most phases of the chassis dynamometer tests, natural gas is combusted more efficiently. This deduction, although not directly substantiated, is in agreement with the characteristics of natural gas and the conversion systems.

The optimization of spark-timing and A/F ratio schedules indicated that part-load energy efficiency could be increased by 2 to 8%, depending on the engine operating conditions and the NG conversion system considered [13]. However, the maximum power delivered with the commercial conversion systems and dealer adjustments could not be improved upon by the engine dynamometer optimization process.

In the Consumers' Gas NG fleet demonstration, a slow/fast-fill CNG fuelling station with a nominal capacity of 110 m^3/h was built, and 22 service vans were converted to operate on a CNG/gasoline dual-fuel mode by using the DFC conversion system. The operation of the station and the fleet was carefully assessed and reported on by Consumers' Gas over a one-year period [14]. The technical and economic information generated in this project was summarized in an MTC report [15].

One of the main purposes of the demonstration was to evaluate the energy efficiency of the demonstration fleet relative to a baseline gasoline fleet. To this end, the fuel consumption of the two fleets operating under urban driving conditions with prolonged idling periods was monitored. The average CNG consumption of the demonstration fleet was found to be 27.2 $m^3/100$ km [15]. The month-to-month variation of the fleet variation was relatively large; however, this variation correlated very well with ambient temperature and constituted a systematic variation. The vehicle-to-vehicle variation in CNG consumption, which constitutes a random variation, was relatively small, i.e., the 90% confidence interval for the average annual vehicle fuel consumption was 0.8 $m^3/100$ km [15]. The average gasoline consumption of the baseline gasoline fleet could not be established with the same degree of accuracy. Thus, although Consumers' Gas predicted a 9% efficiency advantage for CNG [14], the fleet data indicate a rather low confidence level for this prediction.

6/ CONCLUSIONS

A chassis dynamometer investigation was carried out to accurately assess the effects of present CNG conversion systems and practices on the energy consumption, exhaust emissions, and acceleration performance of a common light-duty commercial vehicle (Ford F-150 pickup truck). To this end, a large number of urban and highway dynamometer tests were conducted, strictly according to the Transport Canada guidelines, with the test vehicle in its baseline and CNG/gasoline dual-fuel configuration, using the two conversion systems (DFC and CFS systems) most commonly purchased in Ontario. Thus, the effects of the conversion systems in the CNG and gasoline modes were measured and compared to the baseline gasoline vehicle performance. Diagnostic measurements of A/F ratio and spark-timing schedules were made to correlate and explain the experimental data. In addition, the dual-curve ICD produced by the Autotronic Control Corp. was evaluated, and the consequences of disabling major exhaust emissions control devices were determined.

The main conclusions of this study are summarized in the following paragraphs. In most cases, no distinction is made between the two systems tested, and the average values of the data are presented, because in many respects the DFC and CFS systems produced comparable results.

1/ The average gasoline consumption of the baseline vehicle is 14.63 and 12.10 L/100 km on the urban and highway driving cycles, respectively. The application of the conversion systems causes urban fuel consumption to increase by 8%. Highway fuel consumption, on the other hand, is not affected. The increase is most pronounced under cold transient driving conditions, especially at idle.

2/ The average natural gas consumption of the dual-fuel vehicle is 14.46 and 11.95 m^3/100 km on the urban and highway driving cycles, respectively. At these levels, the average energy consumption of the dual-fuel vehicle in its natural gas mode is 2.5% higher than that of the baseline gasoline vehicle in both urban and highway driving. At cruise (50 and 100 km/h) 3.5 to 4.5% more energy appears to be consumed with natural gas. However, at idle this trend is reversed, and energy consumption decreases by 10 to 11%.

3/ The switch to natural gas results in a noticeable performance drop. The dual-fuel vehicle running on natural gas takes 15 to 20% longer to accelerate from 0 to 100 km/h than the baseline gasoline vehicle.

4/ The effect of vehicle conversion on exhaust emission levels is significant. The dual-fuel vehicle in its gasoline mode produces more HC

and CO and less NO_x. In its natural gas mode, it produces more HC and less CO and NO_x than the gasoline baseline; the HC level exceeds slightly the Canadian exhaust emission standard. The A/F ratio schedules of the two vehicles are appreciably different and thus result in somewhat different emission levels. The DFC system, being calibrated leaner, produces, in general, less pollution.

5/ In an effort to simulate possible tampering with exhaust emission control devices, the EGR and air injection systems of the vehicle were disabled individually. Both of these actions did not produce any significant fuel consumption and acceleration performance benefits. However, they resulted in unacceptably high levels of NO_x and CO pollution with both gasoline and natural gas.

6/ The use of the dual-curve ICD was compared with advancing static timing by 10°. In the natural gas mode, the ICD produces substantial acceleration performance and pollution control benefits; however, it results in a 3.2% fuel consumption increase. In the gasoline mode, the ICD does not provide any benefits.

7/ These conclusions are in qualitative agreement with the engine dynamometer and fleet test results generated at the University of Toronto and the Consumers' Gas Co. However, there are some discrepancies. In particular, the engine dynamometer results indicate a larger efficiency loss in the combustion of natural gas under steady-state conditions, which is not representative of the chassis dynamometer data obtained, mainly under transient engine operating conditions. These observations may be explained by the lower efficiency of combusting natural gas under basically gasoline engine operating conditions. They also point to the potential benefits of natural gas under transient operating conditions.

7/ REFERENCES

[1] Moore, N.P.W., and Roy, B.N., "Comparative Studies of Methane and Propane as Engine Fuels," Proc. of the Institute of Mechanical Engineers, Vol. 170, p. 1137, 1956.

[2] Kuivaneu, G.J., et al, "Engine Fuel Relationships with LPG and Natural Gas," SAE 670053, 1967.

[3] Karim, G.A., et al, "Knock in Dual-Fuel Engines," Proc. of the Institute of Mechanical Engineers, Vol. 181, p. 453, 1967.

[4] Karim, G.A., and Ali, A.I., "Combustion, Knock and Emission Characteristics of a Natural Gas Fuelled Spark Ignition Engine with Particular Reference to Low Intake Temperature Conditions," Proc. of the Institute of Mechanical Engineers, Vol. 189, 1975.

[5] Karim, G.A., et al, "Considerations of Ignition Lag and Combustion Time in a Spark Ignition Engine Using a Data Acquisition System," SAE 820758, 1982.

[6] Karim, G.A., and Wierzba, I., "Comparative Studies of Methane and Propane as Fuels of Spark Ignition and Compression Ignition Engines," SAE 831196, 1983.

[7] Genslak, S.L., "Evaluation of Gaseous Fuels for Automobiles," SAE 720125, 1972.

[8] Fleming, R.D., and Allsup, R.D., "Natural Gas as an Automotive Fuel, An Experimental Study," US Bureau of Mines Report of Investigations, 7806, 1973.

[9] Marshall, W.F., "Potential for Improving Short-Trip Fuel Economy by Fuel Formulation," SAE 790655, 1979.

[10] "Transport Canada -- Voluntary Motor Vehicle Fuel Consumption Program Guidelines 1979."

[11] "Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines," US Federal Register, Vol. 42, No. 124, 1977.

[12] Perfect, N., "An Exhaust Emissions and Fuel Economy Testing Laboratory for Light Vehicles," Ontario Ministry of Transportation, LAB-81-01, May 1981.

[13] Segal, L., and Keffer, J.F., "Testing and Evaluation of Automotive Natural Gas Conversion Equipment -- Phase 1," Ontario Ministry of Transportation, NG-84-03, June 1984.

[14] Consumers' Gas Co. Ltd., "Demonstration of CNG Utilization in Private Sector Fleets -- Final Report," Ontario Ministry of Transportation, NG-84-01, March 1984.

[15] Topaloglu, T., "Natural Gas as an Automotive Fuel: An Analysis of the Consumers' Gas Demonstration Program," Ontario Ministry of Transportation, NG-84-02, April 1984.

Table 1/ Some Physical and Combusion Properties of Methane

Property	
Molecular weight (kg/mol)	16.04
Triple point temperature, K	90.68
Normal boiling point (NBP) temperature, K	111.63
Critical pressure, kPa	4599
Critical temperature, K	190.56
Specific gravity at NTP relative to air	0.55
Density of liquid at NTP, kg/L	0.422
Density of gas at NTP, kg/m^3	0.651
Density of liquid at NBP, kg/L	0.423
Density of vapour at NBP, kg/m^3	1.82
Density ratio: NBP liquid/NTP gas	649
Heat of vaporization, kJ/kg	510
Heat of combustion (low), kJ/kg	50.02
Heat of combustion (high), kJ/kg	55.53
Specific heat (C_p) of NTP, kJ/kg.K	2.22
Specific heat (C_p) of NBP liquid, kJ/kg.K	3.50
Specific heat ratio (C_p/C_v) of NTP gas	1.308
Quenching gap in NTP air, mm	2.03
Limits of flammability in air, vol. %	5.3 to 15
Limits of detonation in oxygen, vol %	6.3 to 13.5
Stoichiometric composition in air, vol. %	9.48
Minimum energy for ignition in air, mJ	0.29
Auto-ignition temperature, K	813
Flame temperature in air, K	2148
Maximum burning velocity in NTP air, cm/s	37 to 45
Energy of stoichiometric mixture, MJ/m^3	3.58

Notes: - NTP stands for 101.325 kPa (1 atm) and 20°C (293.15 K))
- From [6]

Table 2/ Vehicle Specifications

Type	Pickup
Make	Ford
Model	F-150
Model Year	1981
Licence No.	HY9-870
Gross Vehicle Weight	2472 kg
Curb Weight	1660 kg
Engine Type	Gasoline; I-6
Engine Size	4.9 L
Transmission Type	A-3
Carburetor Type	1 BBL
Oxidation Catalyst	Yes
Air Injection	Yes
Exhaust Gas Recirculation	Yes
Evaporation Canister	Yes
Positive Crankcase Vent	Yes
Tires, Front	Firestone 721 P235-75R15
Tires, Back	Firestone M8S P235-75R15

Table 3/ Baseline Vehicle Diagnostics

Curb Idle, rpm	550
Basic Timing at Idle, °BTDC	10
Basic Timing at 2500 rpm, °BTDC	48
Idle HC Emissions, ppm	20
Idle CO Emissions, %	0.02

Table 4/ Test Fuel Specifications

GASOLINE	
Specific Gravity at 21°C	0.740
Reid Vapour Pressure at 38°C, kPa	63
Boiling Point Range:	
Initial Boiling Point, °C	30
10%	49
20%	62
50%	100
90%	168
Final Boiling Point, °C	208
Recovery, %	98.5
Residue, %	1.0
Loss, %	0.5
Heat of Combustion (low), MJ/L	32.4
Heat of Combustion (low), MJ/kg	43.8

NATURAL GAS	
Composition, %	
CH_4	95.5
C_2H_6	2.0
C_3H_8	0.1
C_4H_{10}	0.01
N_2	1.8
CO_2	0.34
Heat of Combustion (low), MJ/m^3	33.6
Heat of Combustion (low), MJ/kg	51.6

Table 5/ Dynamometer Parameters

	Average	Standard Development
Inertia Weight, lb	4000	
Indicated Road Load, hp	12.7	
Actual Road Load, hp	15.0	
Tire Pressure, kPa	310	
Cell Temperature, °C	26.8	
Cell Humidity, gr/lb	24.8	3.8
Cell Pressure, kPa	100.0	0.6

Table 6/ Gasoline Consumption and Performance of the Test Vehicle (MTO Chassis Dynamometer Test Results)

		DUAL-FUEL CONFIGURATION		
	Baseline	DFC-System	CFS-System	Average
FUEL CONSUMPTION (L/100 km)				
Urban Cycle	14.63	15.61	15.84	15.79
Cold Transient Phase	14.79	17.21	17.42	17.32
Stabilized Phase	14.77	15.36	15.70	15.53
Hot Transient Phase	14.23	14.83	14.88	14.86
Highway Cycle	12.10	11.97	12.28	12.13
Combined (Urban & Hwy.)	13.49	13.97	14.24	14.14
Steady-State Operation				
Idle, in "Drive" (L/h)	2.05	2.56	2.57	2.57
Idle, in "Park" (L/h)	2.07	2.44	2.45	2.45
50 km/h	8.69	9.39	8.79	9.09
100 km/h	13.46	13.57	13.53	13.55
ACCELERATION PERFORMANCE (s)				
0-100 km/h, in "Drive"	14.9	13.4	16.9	15.2
0-100 km/h, in "Second"	16.0	14.5	19.0	16.8

Table 7/ Natural Gas Consumption and Performance of the Test Vehicle (MTO Chassis Dynamometer Test Results)

	DFC Kit-1	DFC Kit-2	CFS Kit	Average
FUEL CONSUMPTION (m^3/100 km)				
Urban Cycle	14.46	14.30	14.62	14.46
Cold Transient Phase	15.20	15.67	16.20	15.69
Stabilized Phase	14.07	14.12	14.43	14.21
Hot Transient Phase	14.57	13.61	13.86	14.01
Highway Cycle	11.81	11.90	12.14	11.95
Combined (Urban & Hwy.)	13.27	13.22	13.50	13.33
Steady-State Operation				
Idle, in "Drive" (m^3/h)	1.73	1.81	1.73	1.76
Idle, in "Park" (m^3/h)	1.79	1.88	1.86	1.84
50 km/h	8.66	8.88	8.51	8.68
100 km/h	14.17	13.41	13.12	13.57
ACCELERATION PERFORMANCE (s)				
0-100 km/h, in "Drive"	17.5	16.8	17.1	17.1
0-100 Km/h, in "Second"	19.9	18.8	19.3	19.3

Note: DFC Kit-1 and DFC Kit-2 refer to the first and second versions of the Diversified Fuel Components Co. kit.

Table 8/ Energy Consumption with Gasoline and Natural Gas (Comparison of Energy Utilization Efficiencies)

GASOLINE				
		Dual-Fuel Configuration		
	Baseline	DFC-System	CFS-System	Average
Urban Driving (MJ/100 km)	474	506	513	510
Highway Driving	392	388	398	393
Cruise, 50 km/h	282	304	285	295
Cruise, 100 km/h	436	440	438	439
Idling, in "Drive" (MJ/h)	66	83	83	83

NATURAL GAS				
	DFC-1	DFC-2	CFS	Average
Urban Driving (MJ/100 km)	486	480	491	486
Highway Driving	397	400	408	402
Cruise, 50 km/h	291	298	286	292
Cruise, 100 km/h	476	451	441	456
Idling, in "Drive" (MJ/h)	58	61	58	59

Note: DFC-1 and DFC-2 refer to the two versions of the Diversified Fuel Components conversion kits, and CFS, to the CNG Fuel Systems conversion kit.

Table 9/ Exhaust Emission Levels with Gasoline (MTO Chassis Dynamometer Test Results)

		DUAL-FUEL CONFIGURATION		
	Baseline	DFC-System	CFS-System	Average
HYDROCARBONS (g/mi)				
Urban Cycle	0.54	0.62	1.21	0.92
Cold Transient Phase	1.03	1.50	3.03	2.27
Stabilized Phase	0.31	0.33	0.60	0.47
Hot Transient Phase	0.61	0.52	0.96	0.74
Highway Cycle	0.13	0.12	0.23	0.18
Combined (Urban & Hwy.)	0.36	0.40	0.77	0.59
CARBON MONOXIDE (g/mi)				
Urban Cycle	3.76	4.51	11.05	7.78
Cold Transient Phase	13.96	17.61	35.80	26.70
Stabilized Phase	0.63	0.25	0.36	0.31
Hot Transient Phase	2.02	2.55	12.60	7.58
Highway Cycle	2.24	0.15	1.21	0.68
Combined (Urban & Hwy.)	2.18	2.55	6.62	4.59
NITROGEN OXIDES (g/mi)				
Urban Cycle	1.57	1.80	1.03	1.42
Cold Transient Phase	1.76	2.45	1.61	2.03
Stabilized Phase	1.14	1.31	0.75	1.03
Hot Transient Phase	2.25	2.16	1.13	1.65
Highway Cycle	2.81	2.75	1.33	2.04
Combined (Urban & Hwy.)	2.13	2.23	1.17	1.70

Table 10/ Light-Duty Vehicle Exhaust Emissions Standards (g/mi)

	HC	CO	NO_x
Canada	2.0	25	3.1
US	0.41	3.4	1.0
California	0.41	7.0	0.4

Table 11/ Exhaust Emission Levels with Natural Gas (MTO Chassis Dynamometer Test Results)

	DFC Kit-1	DFC Kit-2	CFS Kit	Average
HYDROCARBONS (g/mi)				
Urban Cycle	3.13	2.05	3.30	2.83
Cold Transient Phase	4.13	2.11	5.29	3.84
Stabilized Phase	2.42	2.07	.14	2.54
Hot Transient Phase	3.89	1.97	2.20	2.69
Highway Cycle	1.67	0.86	1.12	1.22
Combined (Urban & Hwy.)	2.47	1.51	2.32	2.11
CARBON MONOXIDE (g/mi)				
Urban Cycle	2.87	0.36	1.11	1.45
Cold Transient Phase	10.14	0.47	4.12	4.91
Stabilized Phase	0.86	0.27	0.20	0.44
Hot Transient Phase	1.36	0.44	0.60	0.80
Highway Cycle	0.43	0.15	0.83	0.47
Combined (Urban & Hwy.)	1.77	0.27	0.98	1.01
NITROGEN OXIDES (g/mi)				
Urban Cycle	1.07	1.03	2.11	1.40
Cold Transient Phase	0.79	1.76	2.63	1.73
Stabilized Phase	1.23	0.48	1.61	1.11
Hot Transient Phase	1.05	1.51	2.69	1.75
Highway Cycle	0.98	1.49	3.19	1.89
Combined (Urban & Hwy.)	1.03	1.24	2.60	1.62

Table 12/ Effects of the Removal of Specific Exhaust Emission Control Measures in the Natural Gas Mode with the DFC Conversion Kit

	Baseline Natural Gas	EGR Removed	Air Injection Removed
FUEL CONSUMPTION			
Urban Cycle (m^3/100 km)	14.30	14.42	14.36
Highway Cycle	11.90	11.84	12.02
Cruise, 50 km/h	8.88	8.90	8.59
Cruise, 100 km/h	13.41	13.32	13.70
Idle, in "Drive" (m^3/h)	1.81	1.70	1.74
EXHAUST EMISSIONS (g/mi)			
HC (Urban Cycle)	2.05	2.44	2.77
(Highway Cycle)	0.86	0.69	1.72
CO (Urban Cycle)	0.36	1.31	15.90
(Highway Cycle)	0.15	0.10	25.39
NO_x (Urban Cycle)	1.03	9.79	1.22
(Highway Cycle)	1.49	12.01	1.08
ACCELERATION PERFORMANCE(s)			
0-100 km/h, in "Drive"	16.8	16.7	17.2
0-100 km/h, in "Second"	18.8	18.9	19.4

Table 13/ Effects of Ignition Control Device (ICD) in Gasoline Mode (MTO Chassis Dynamometer Test Results)

	Baseline	CFS-System with ICD	CFS-System Without ICD
FUEL CONSUMPTION (L/100 km)			
Urban Cycle	14.63	15.84	14.92
Highway Cycle	12.10	12.28	13.23
Combined (Urban & Hwy.)	13.49	14.24	14.16
ACCELERATION PERFORMANCE (s)			
0-100 km/h, in "Drive"	14.9	16.9	15.7
0-100 km/h, in "Second"	16.0	19.0	17.2
HYDROCARBONS (g/mi)			
Urban Cycle	0.54	1.21	1.31
Highway Cycle	0.13	0.23	0.24
CARBON MONOXIDE (g/mi)			
Urban Cycle	3.76	11.05	14.62
Highway Cycle	0.24	1.21	9.08
NITROGEN OXIDES (g/mi)			
Urban Cycle	1.57	1.03	1.23
Highway Cycle	2.81	1.33	1.23

Table 14/ Effects of Ignition Control Device (ICD) in Natural Gas Mode (MTO Chassis Dynamometer Test Results)

	CFS-System with ICD	CFS-System Without ICD
FUEL CONSUMPTION (m^3/100 km)		
Urban Cycle	14.62	14.36
Highway Cycle	12.14	11.49
Combined (Urban & Hwy.)	13.50	13.07
ACCELERATION PERFORMANCES (s)		
0-100 km/h, in "Drive"	17.1	18.7
0-100 km/h, in "Second"	19.3	21.3
HYDROCARBONS (g/mi)		
Urban Cycle	3.30	8.25
Highway Cycle	1.12	2.03
CARBON MONOXIDE (g/mi)		
Urban Cycle	1.11	2.90
Highway Cycle	0.83	0.07
NITROGEN OXIDES (g/mi)		
Urban Cycle	2.11	0.88
Highway Cycle	3.19	1.20

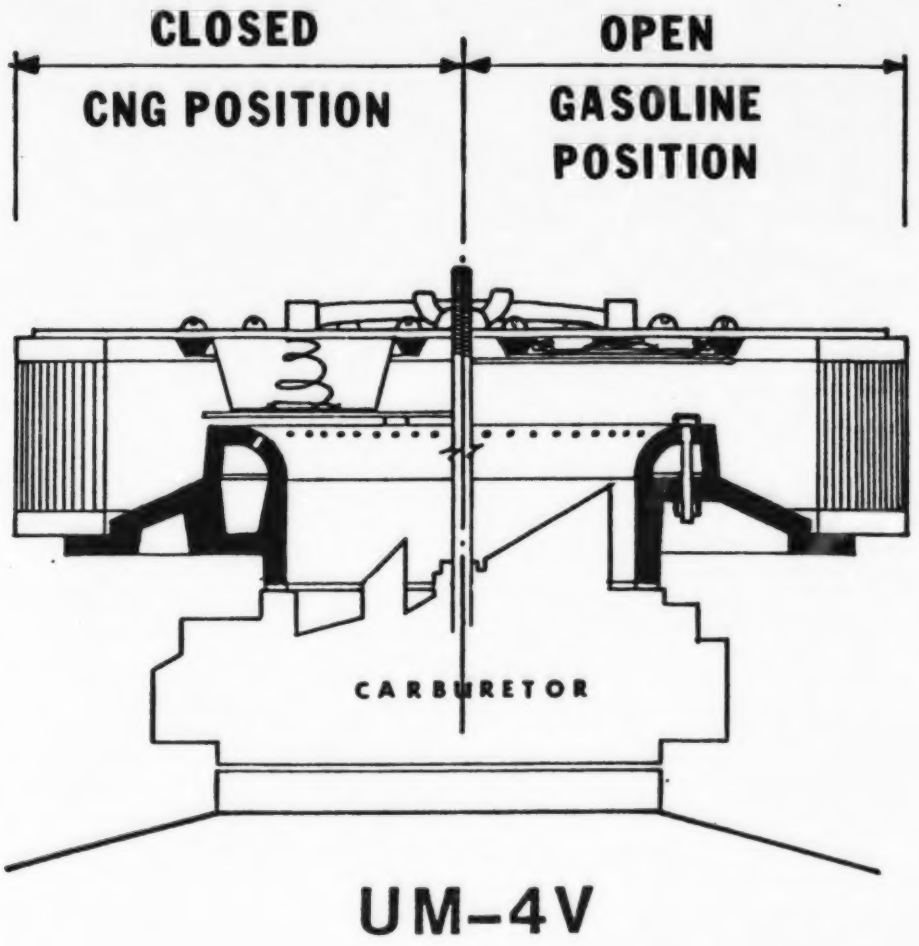


Figure 1/ Air-Fuel Mixer of the Diversified Fuel Components Co.

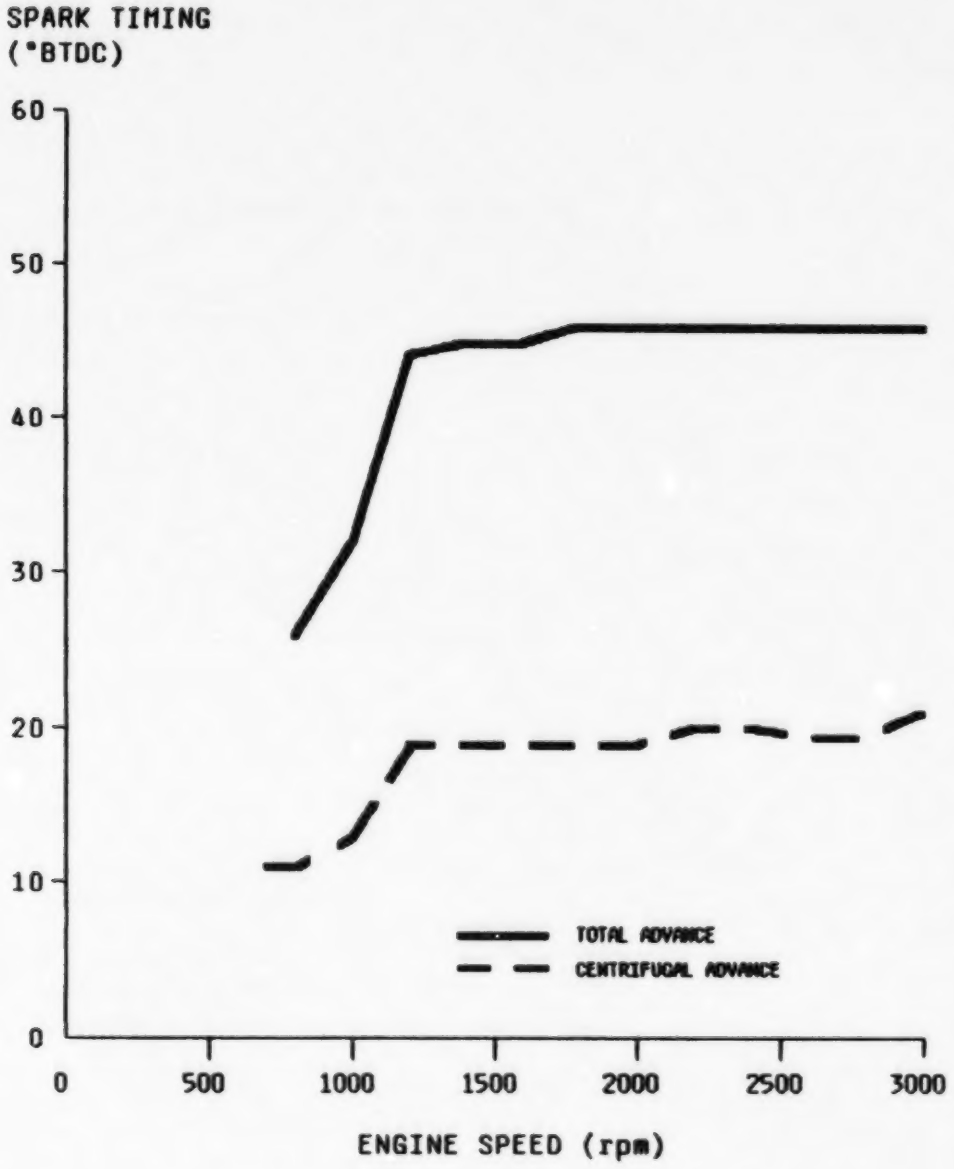


Figure 2/ Spark-Timing Curves of Baseline Gasoline Vehicle

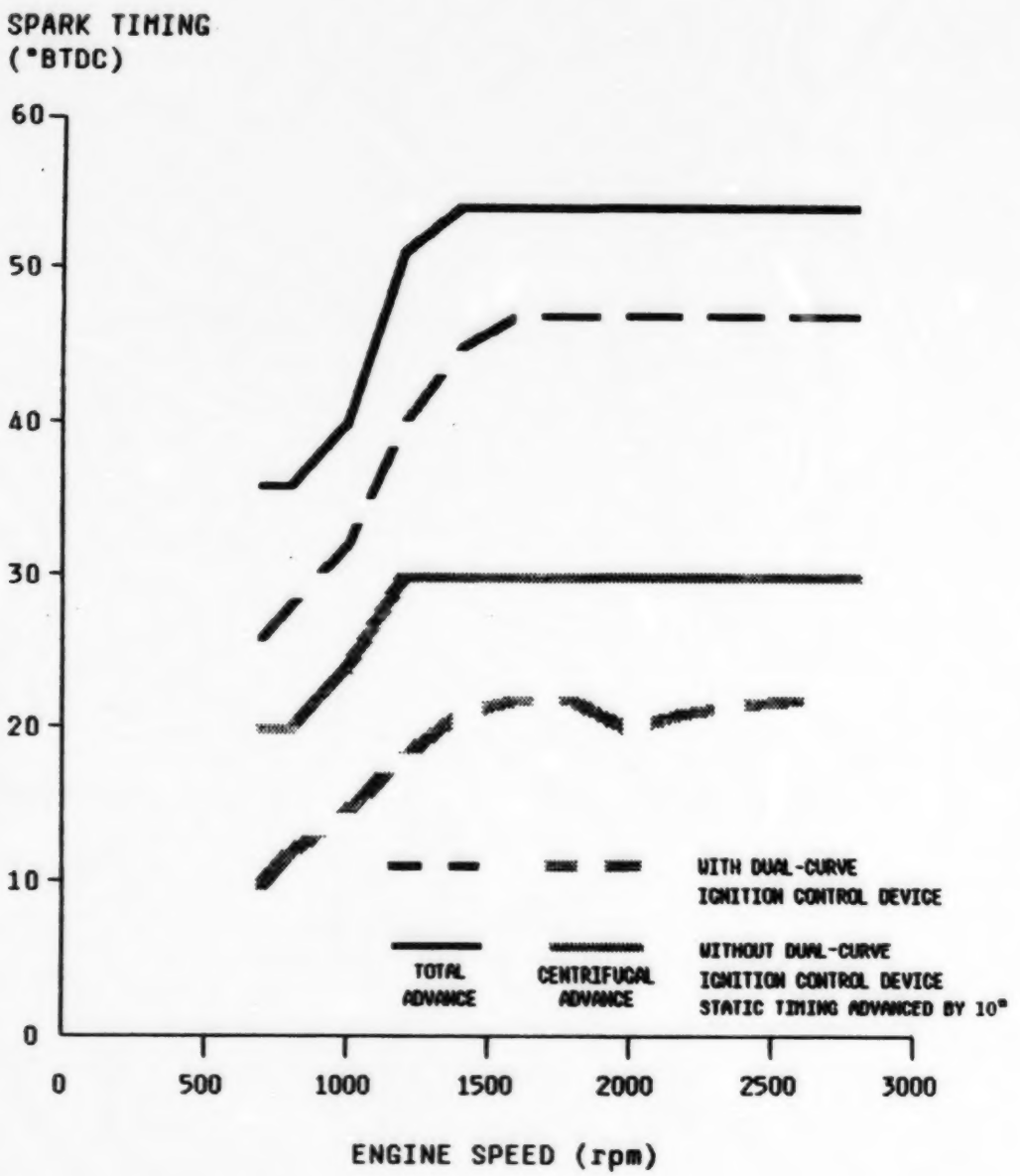


Figure 3/ Spark Timing of Dual-Fuel Vehicle in the Gasoline Mode

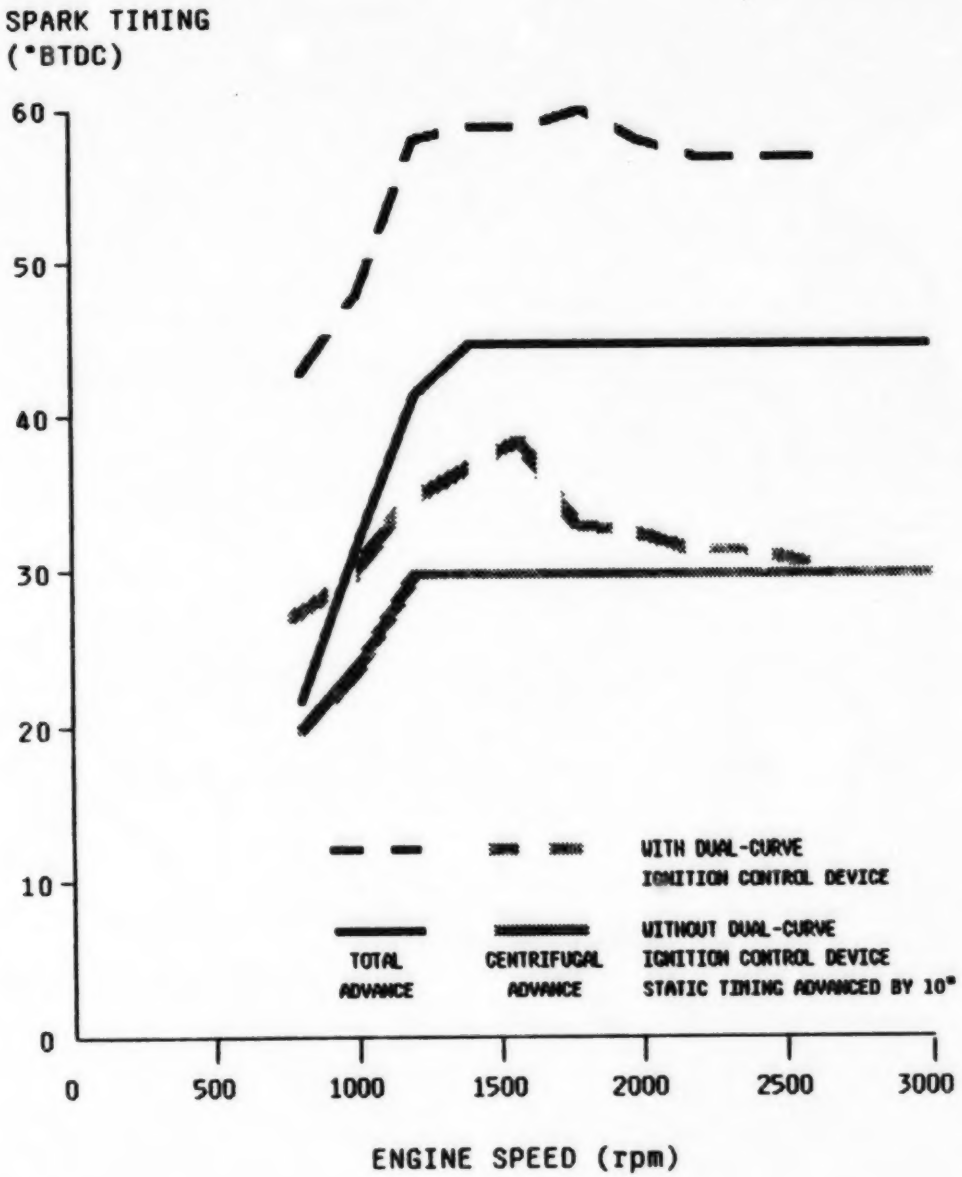


Figure 4/ Spark Timing of Dual-Fuel Vehicle in the CNG Mode

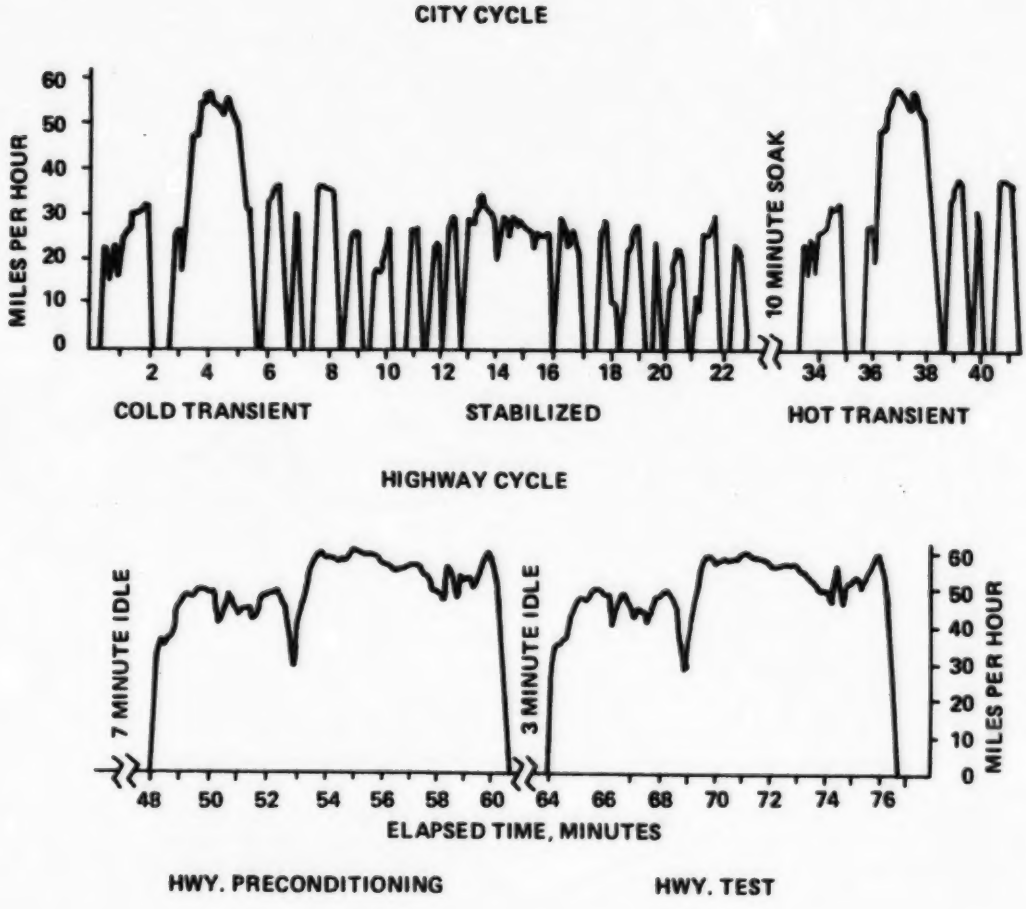


Figure 5/ City (Urban) and Highway Driving Cycles

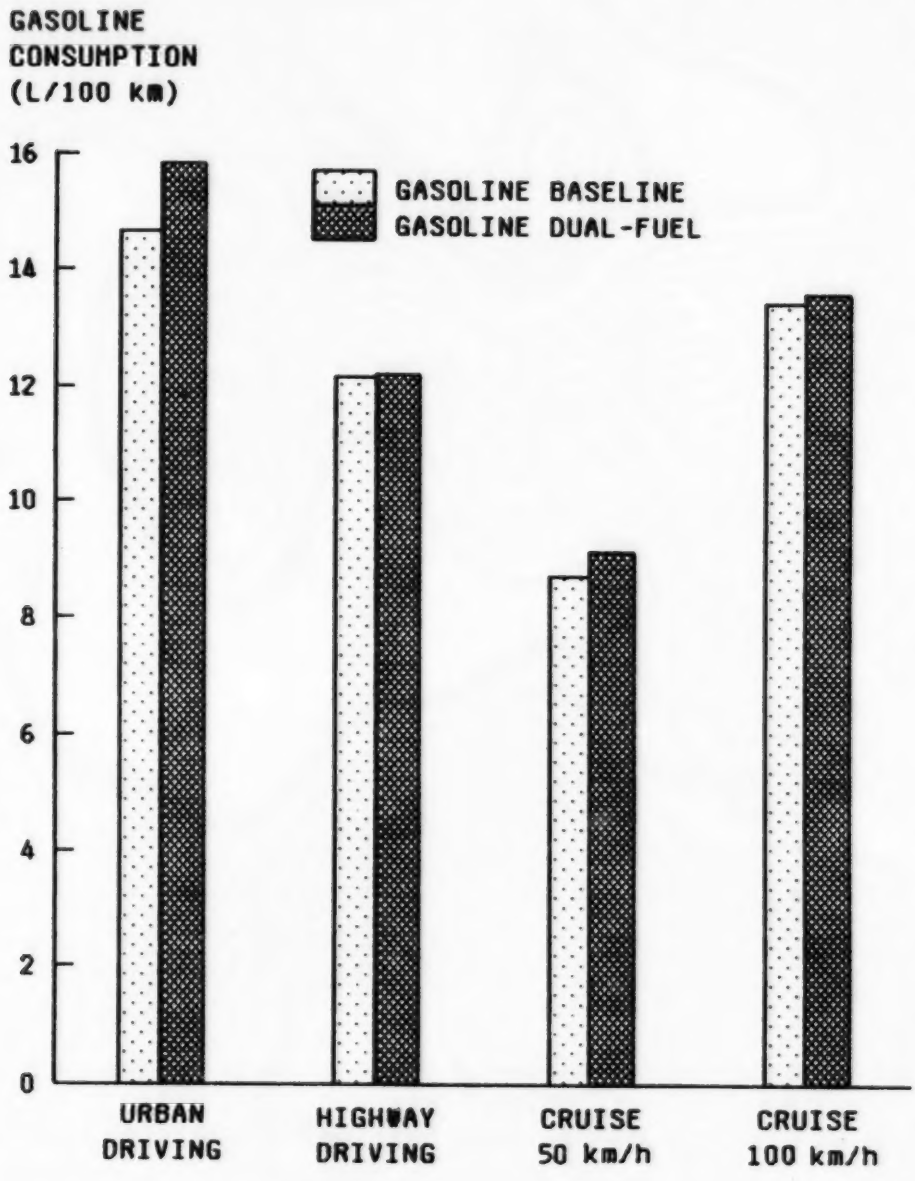


Figure 6/ Gasoline Consumption in the Baseline and Dual-Fuel Modes

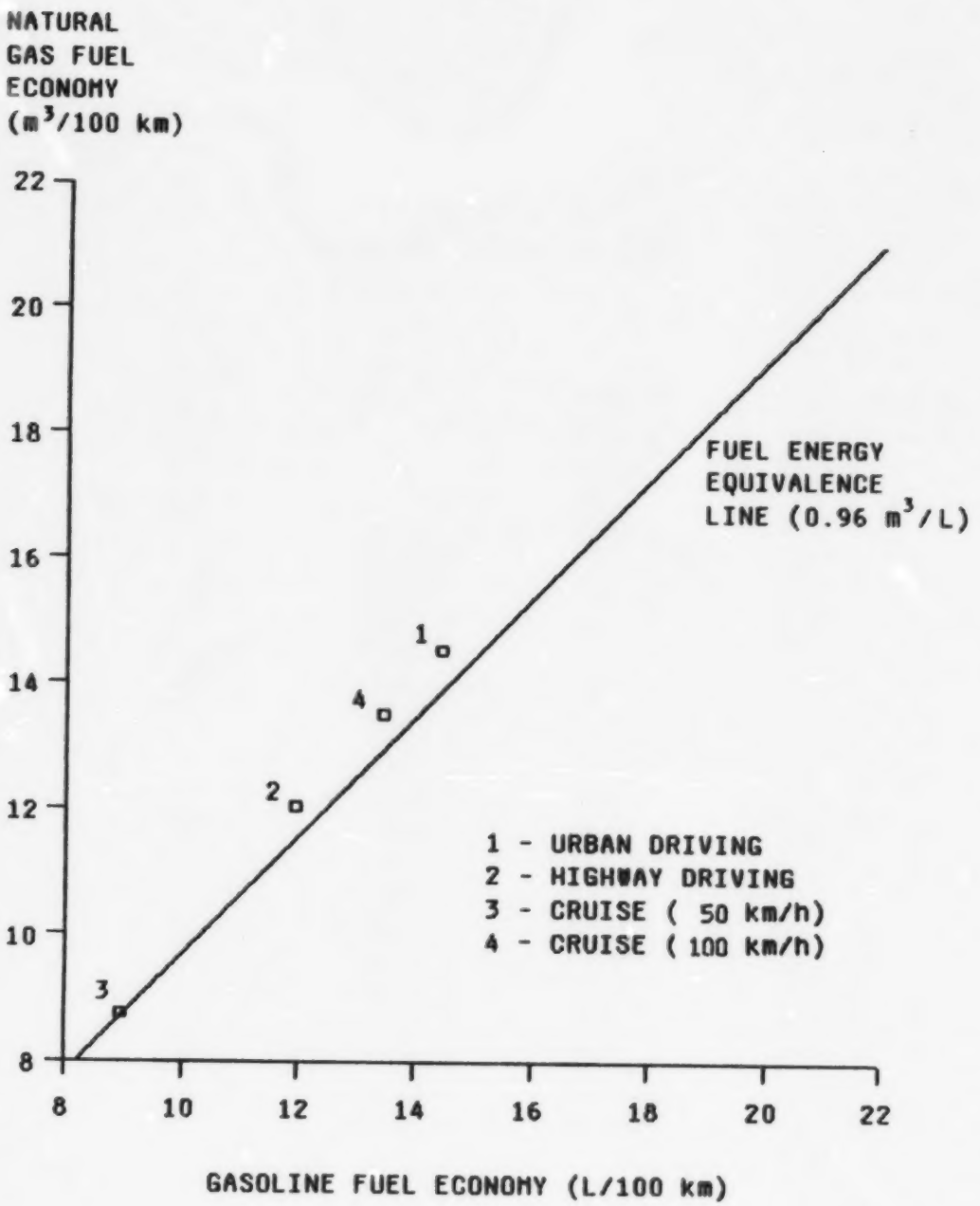


Figure 7/ Comparison of Natural Gas and Gasoline Combustion Efficiencies

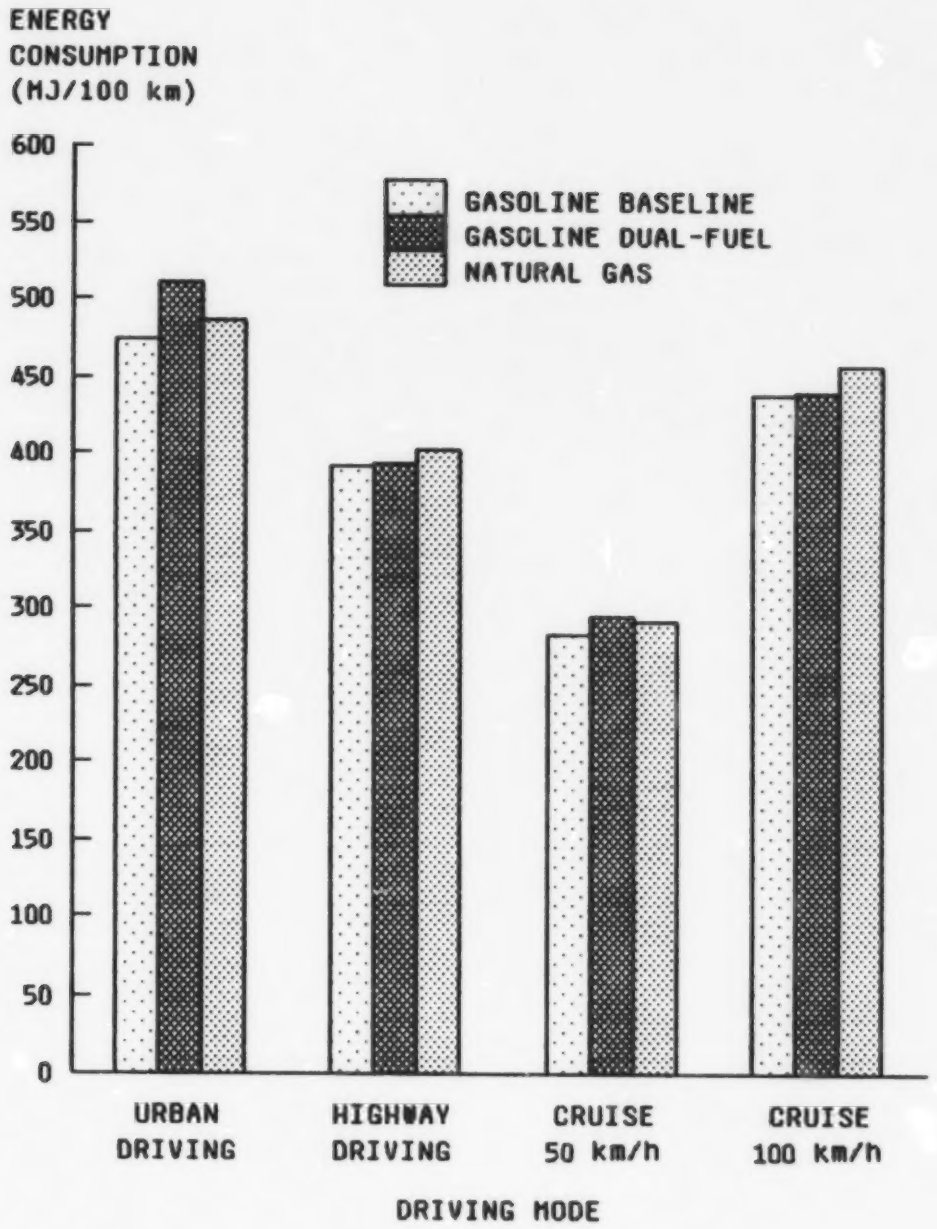


Figure 8/ Energy Consumption with Gasoline and Natural Gas

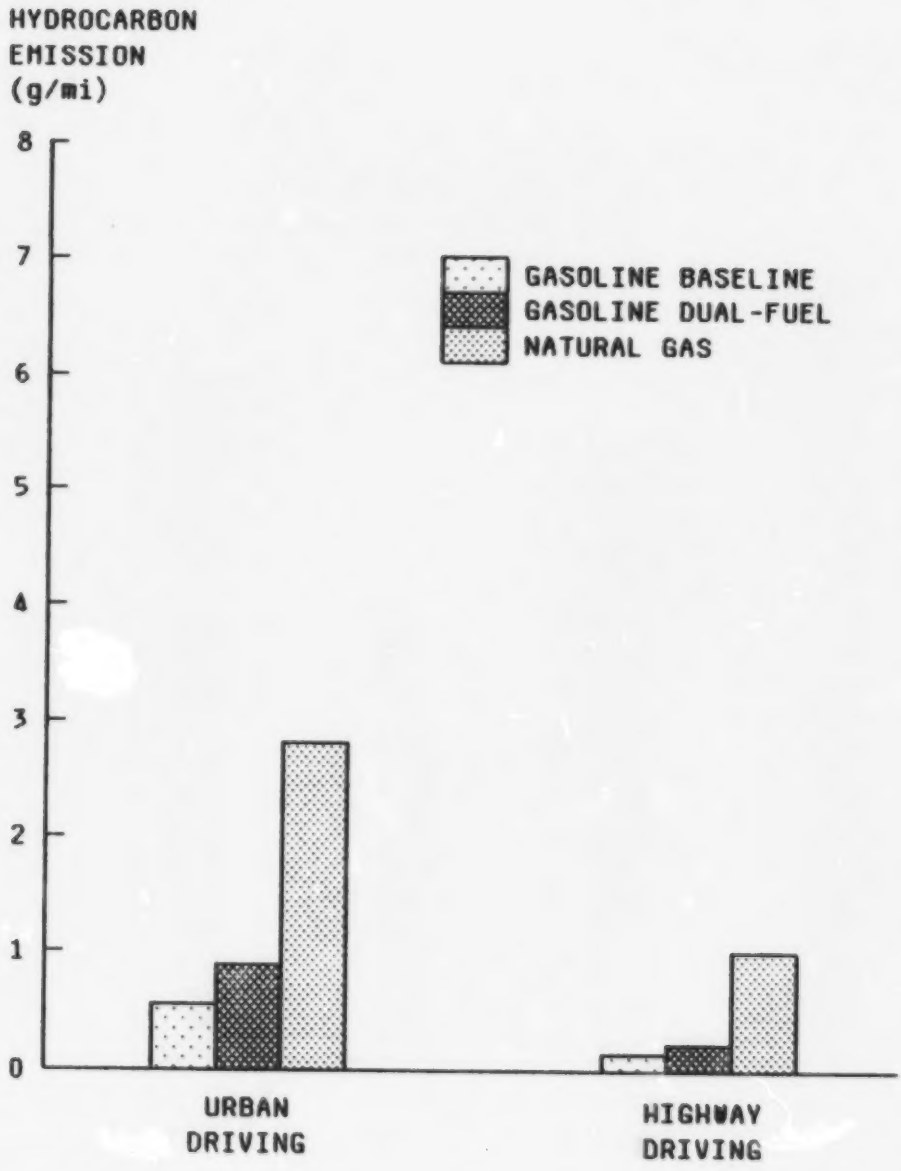


Figure 9/ Hydrocarbon Emissions with Gasoline and Natural Gas

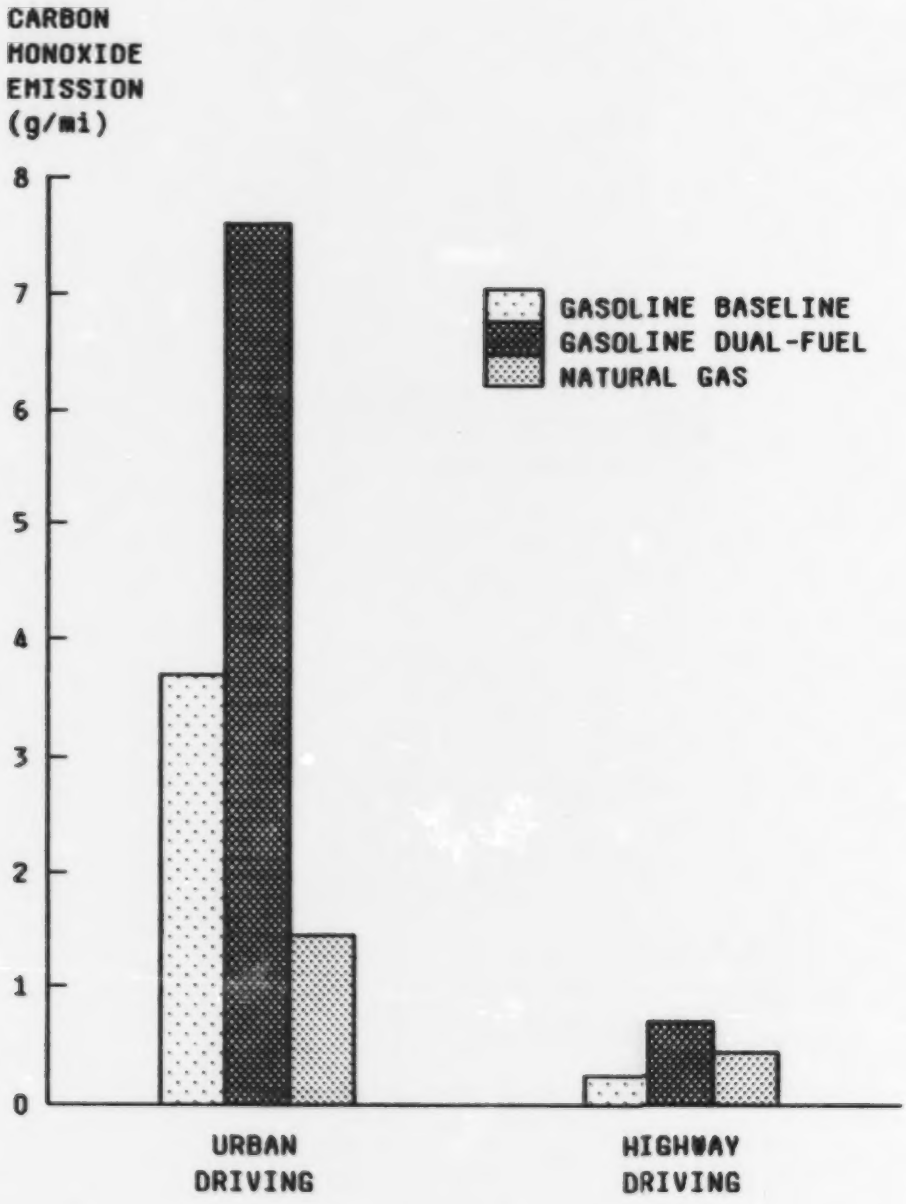


Figure 10/ Carbon Monoxide Emissions with Gasoline and Natural Gas

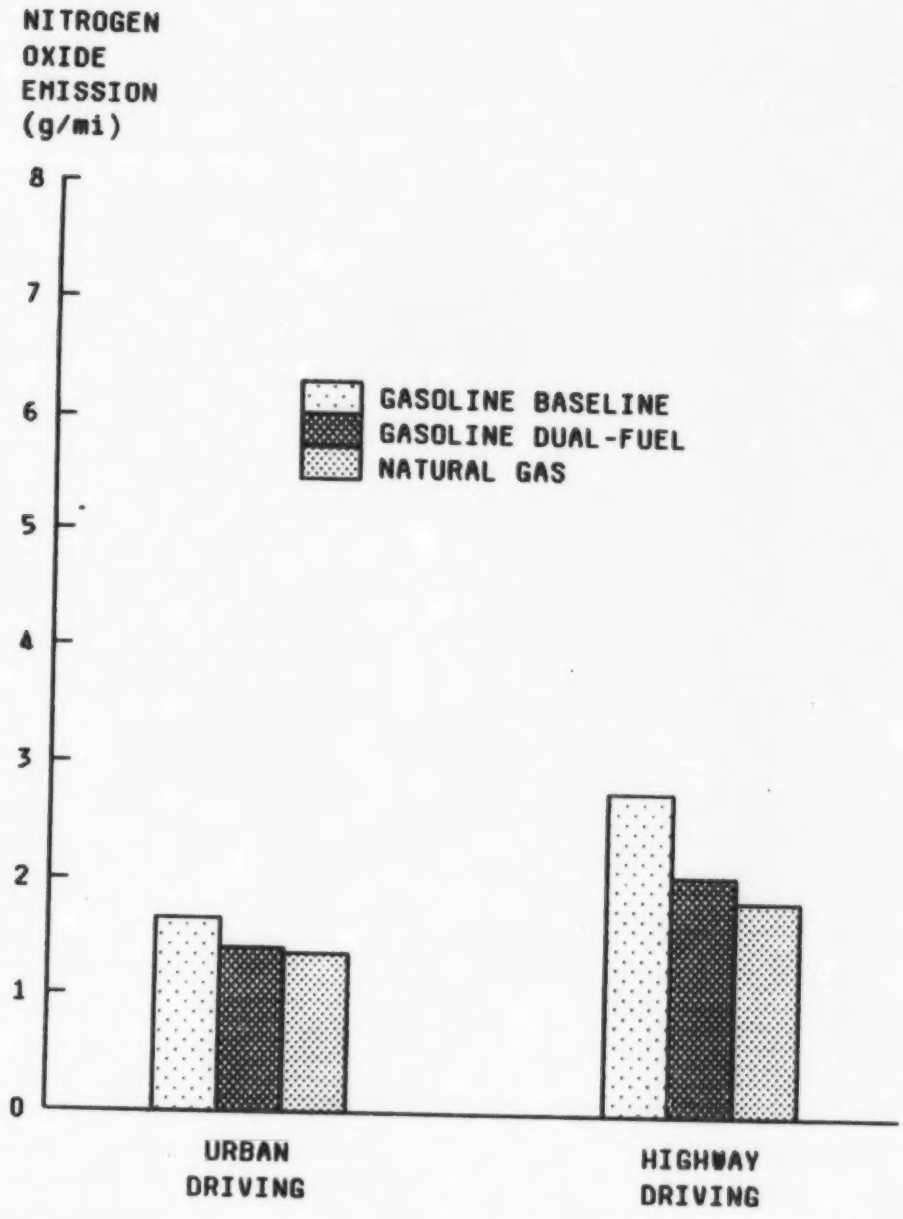


Figure 11/ Nitrogen Oxide Emissions with Gasoline and Natural Gas

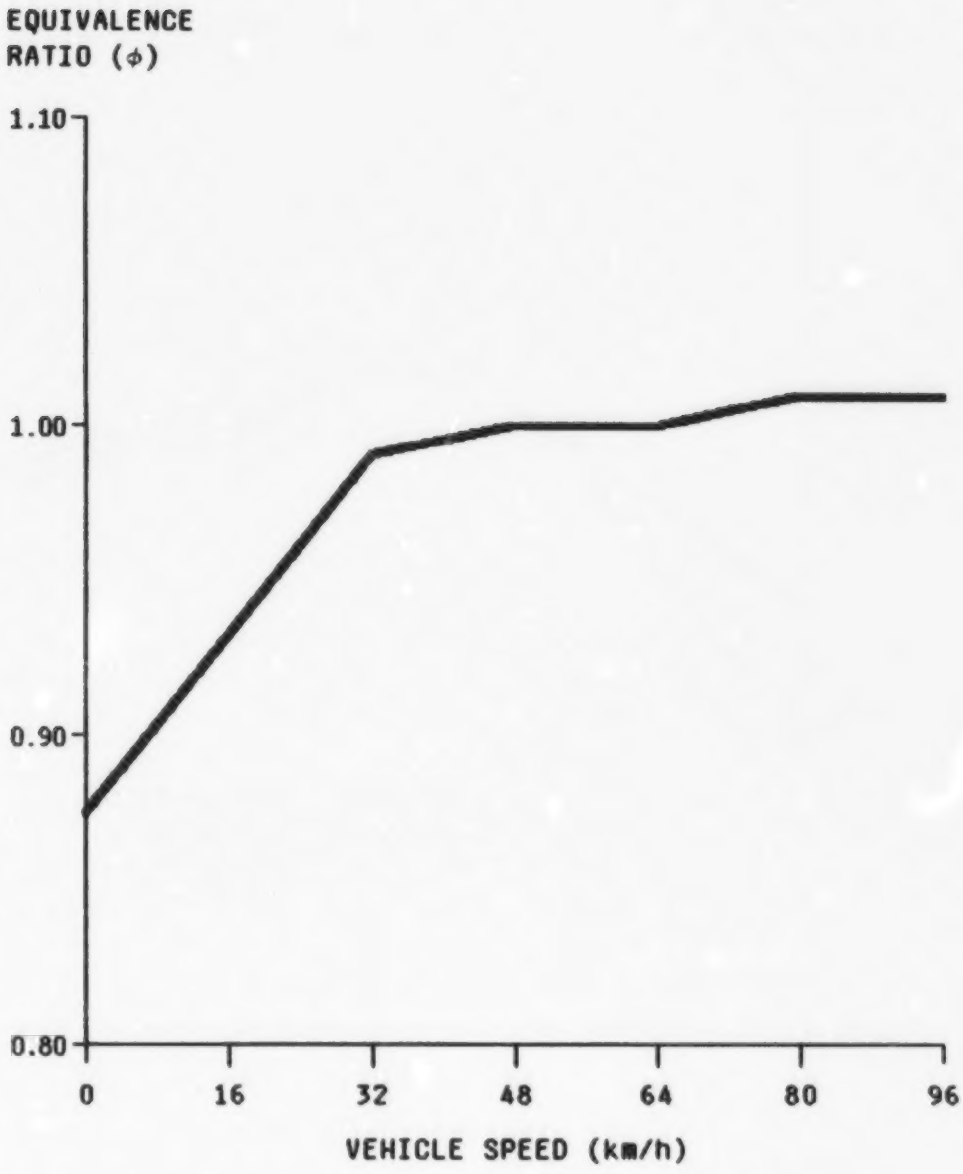


Figure 12/ Variation of the Air-Fuel Mixture Equivalence Ratio (ϕ) with Vehicle Speed (Baseline Gasoline Mode)

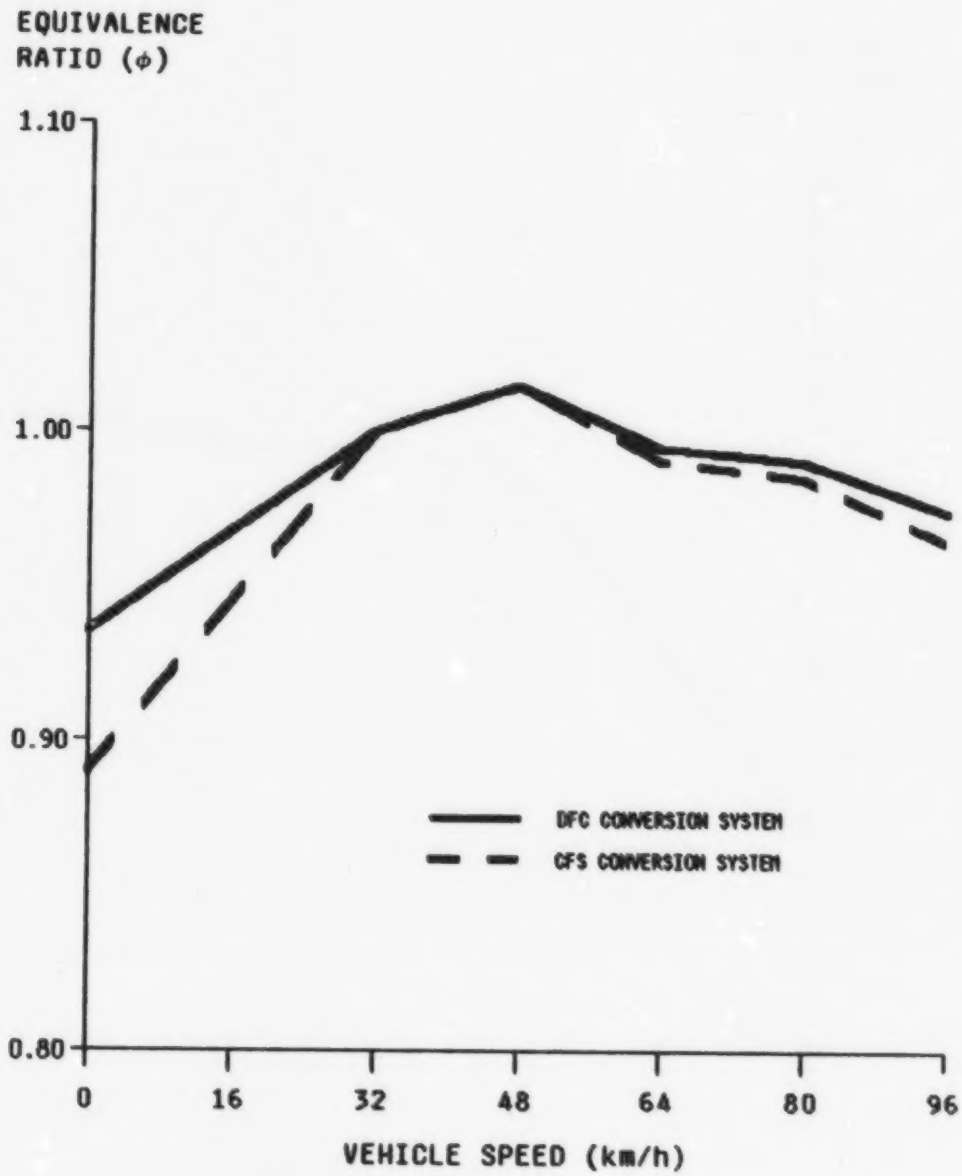


Figure 13/ Variation of the Air-Fuel Mixture Equivalence Ratio (φ) with Vehicle Speed (Dual-Fuel Vehicle in the Gasoline Mode)

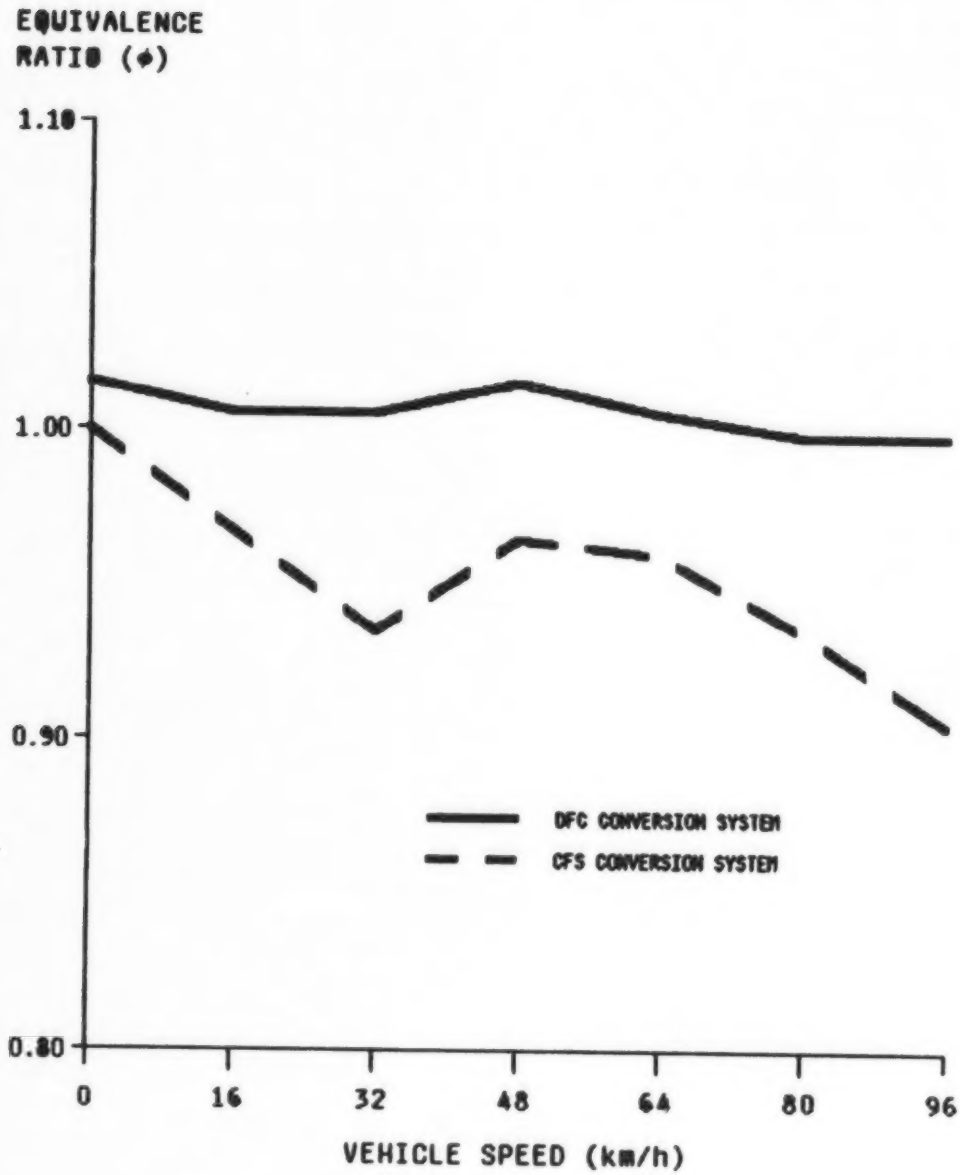


Figure 14/ Variation of the Air-Fuel Mixture Equivalence Ratio (ϕ) with Vehicle Speed (Dual-Fuel Vehicle in the Natural Gas Mode)